Experiment of Λn Interaction Measurement via the Final State Interaction in $\gamma d \to K^+ \Lambda n$ Reaction

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for the NKS2 Collaboration

Department of Physics, Graduate School of Science, Tohoku University

2019/May/20

Radiation-Lab Seminar

Overview

- Motivation of Λn interaction measurement
- NKS2 experiment at ELPH, Tohoku Univ.
- Λn final-state-interaction study by NKS2
- Detector R&D
- Summary of Λn FSI exp.
- The other projects in Tohoku ELS group
  - JLab, Mainz, ELPH

Motivation

- Study of nuclear force
  - Baryon-Baryon interaction including strangeness
  - Experimental study
    - Spectroscopy of Hypernuclei
      - lots of data
    - ΛN scattering experiment at low energies
      - poor and limited accuracy of Λp data
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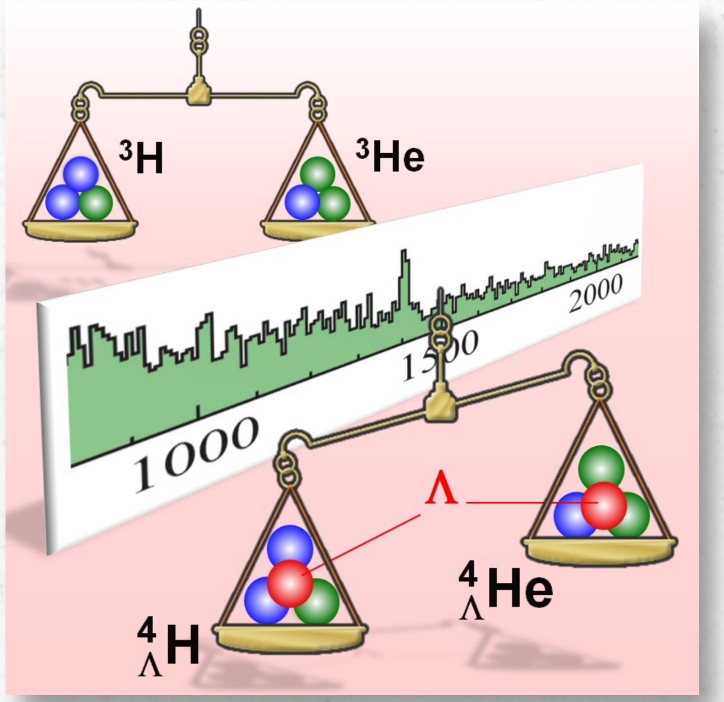

Figure from Prof. Tamura

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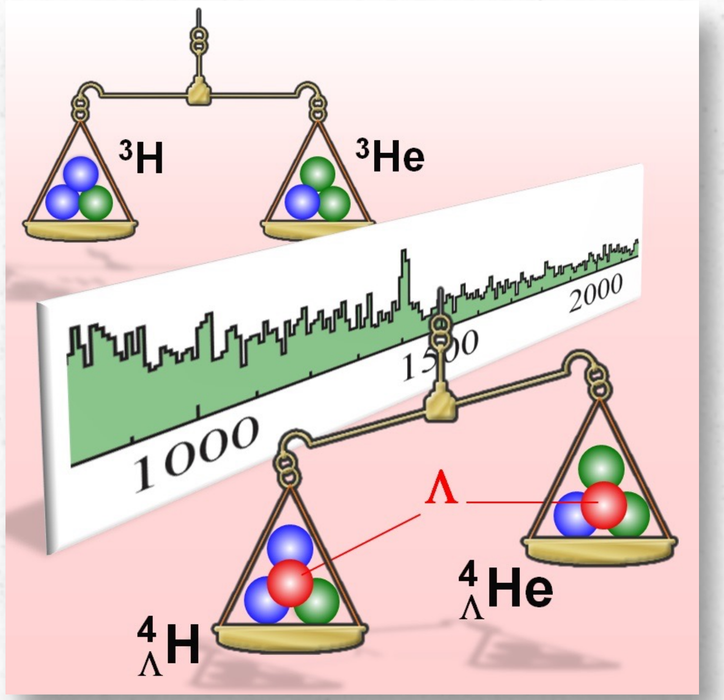

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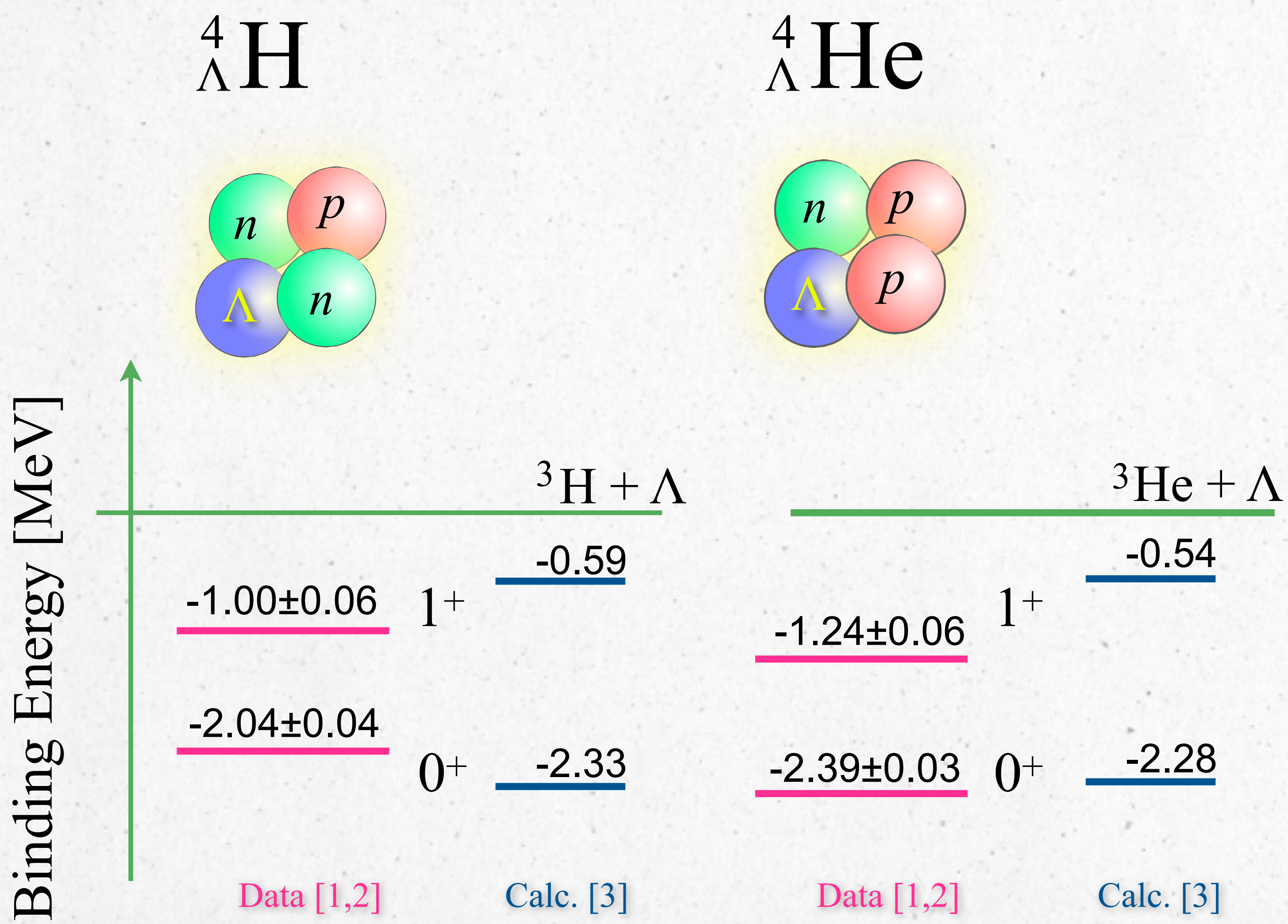
- K^+ cross section in $\gamma d \to K^+ \Lambda n$ reaction
  - Modification by FSI effect of Λn

Problem in ΛN Interaction

- Charge symmetry breaking (CSB) in the *ΛN* interaction



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Energy scheme of A=4 Λ hypernuclei
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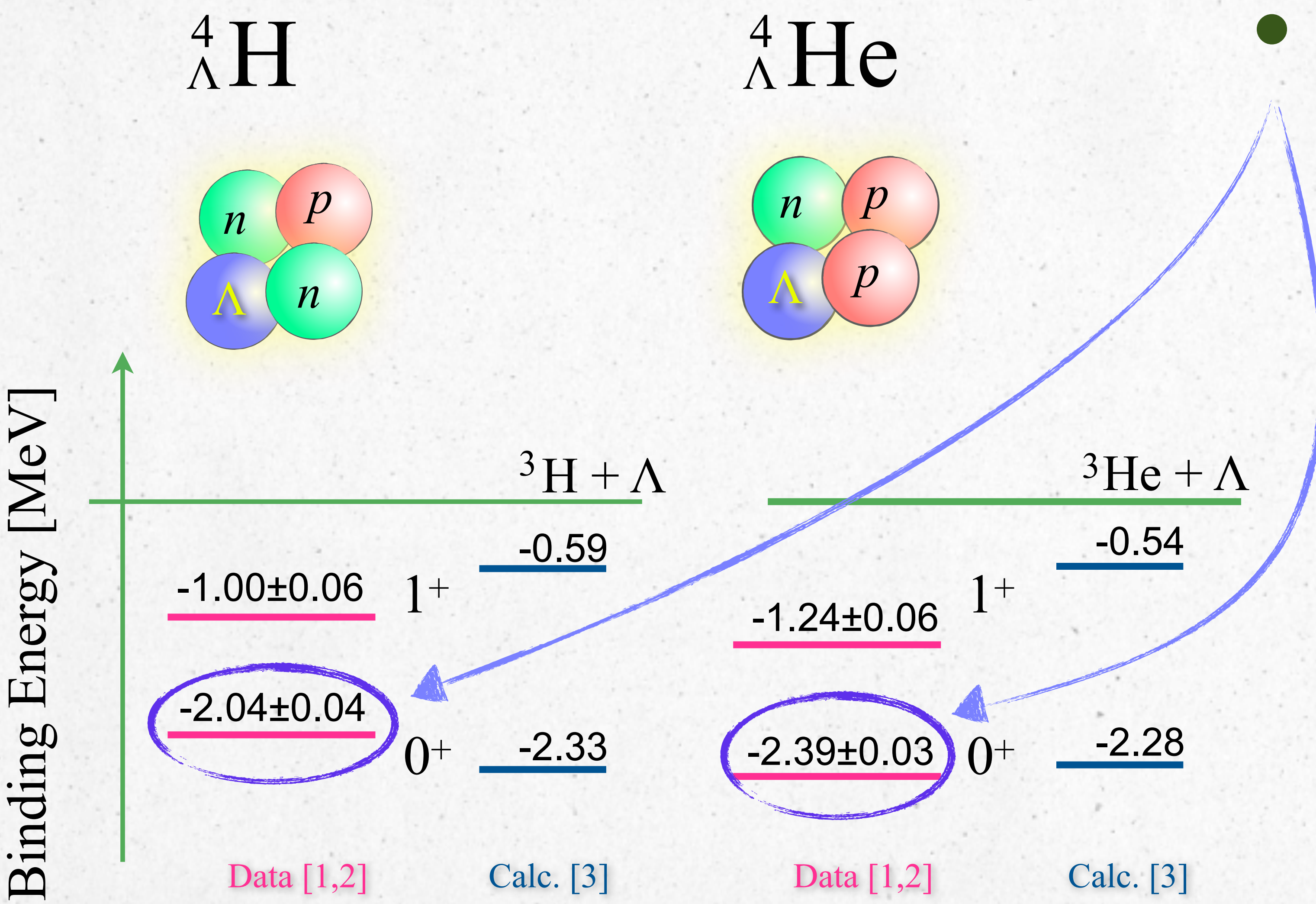

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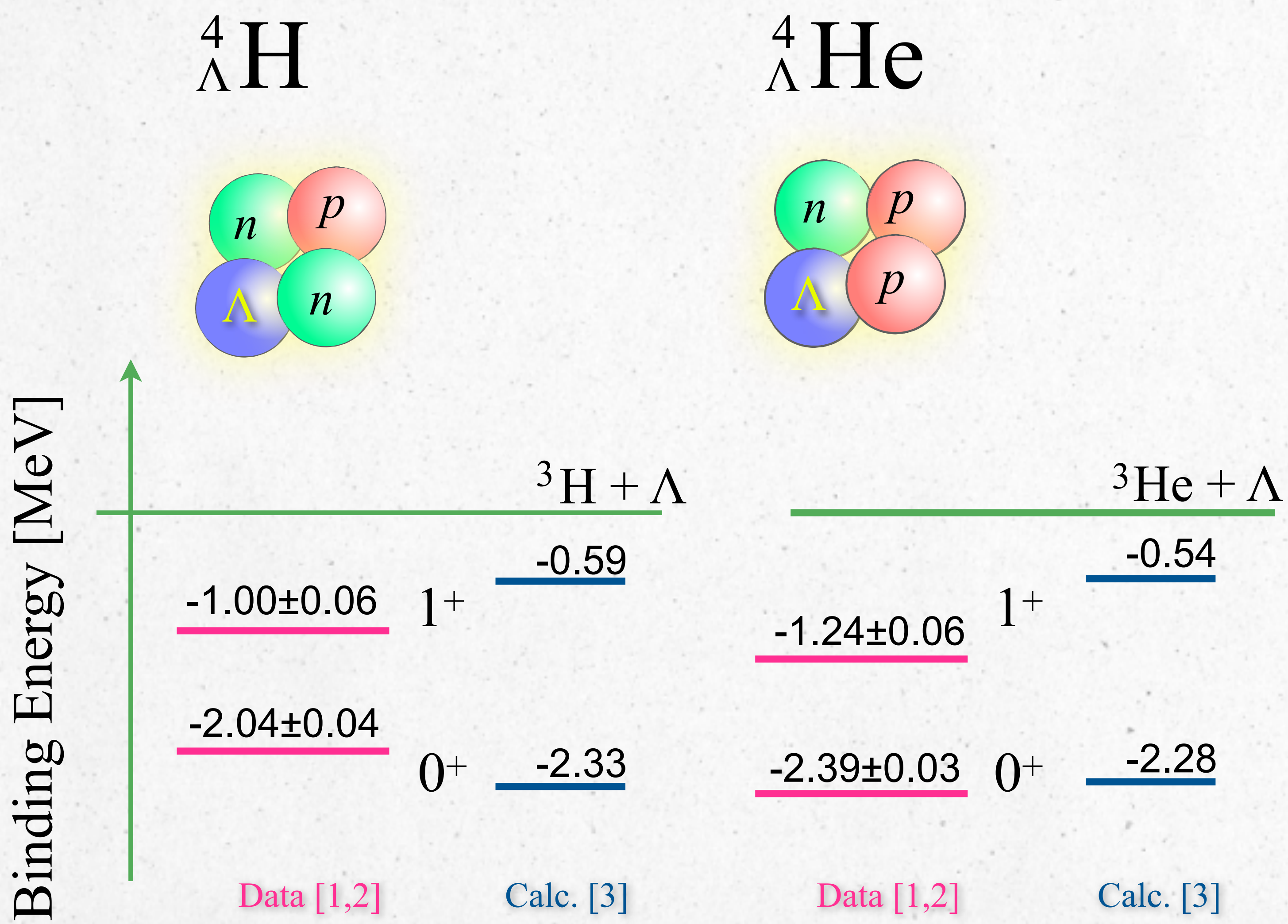

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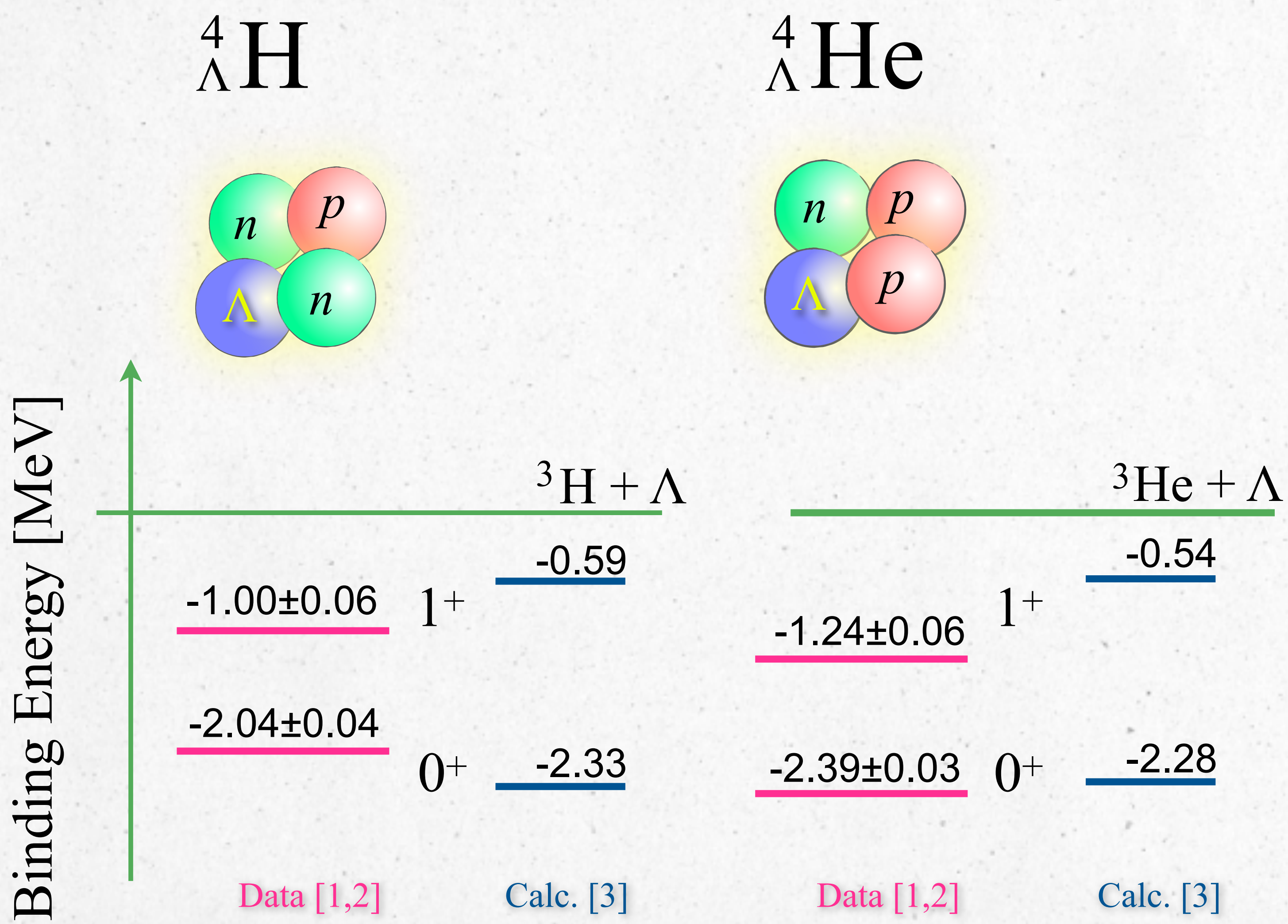

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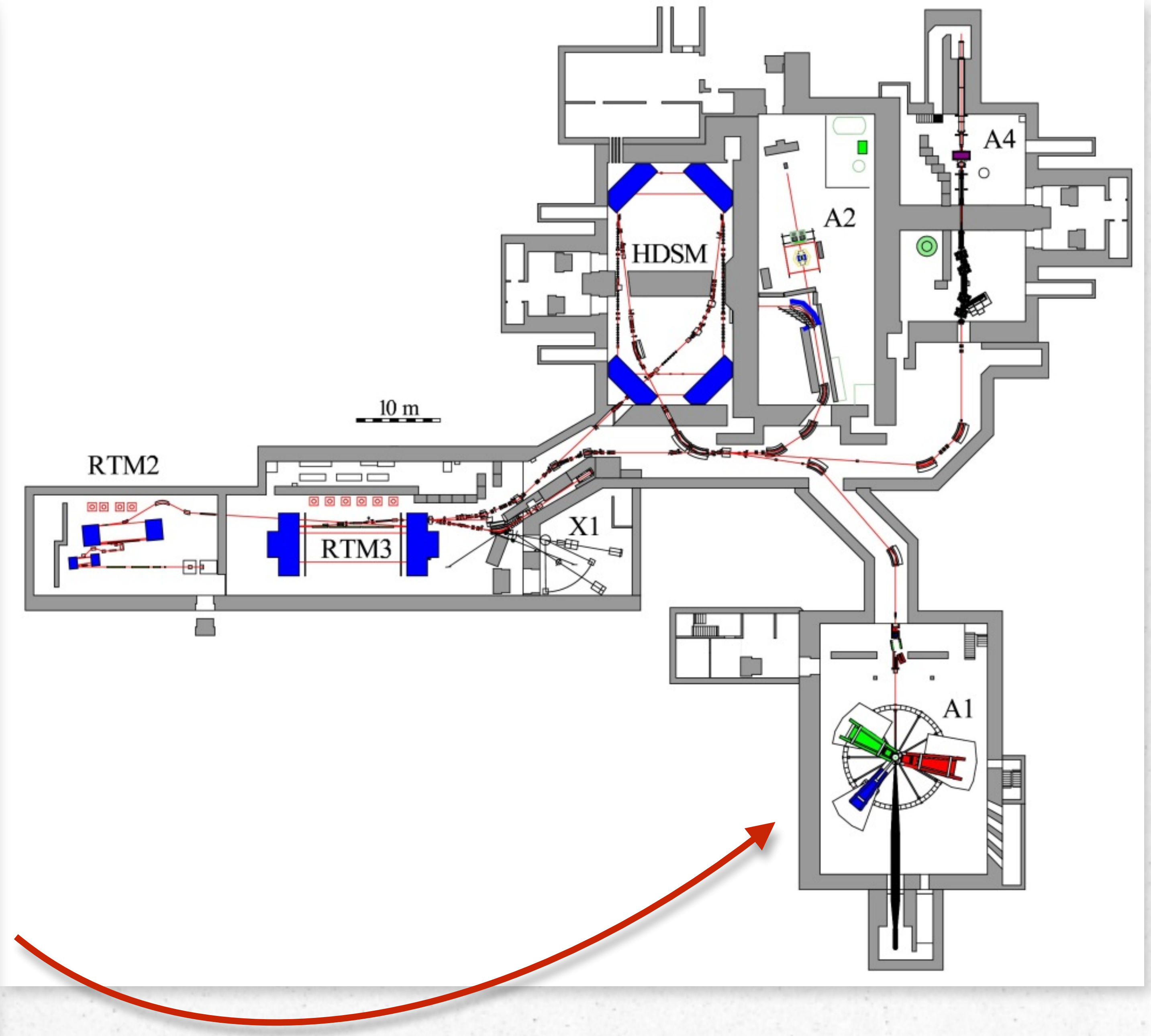
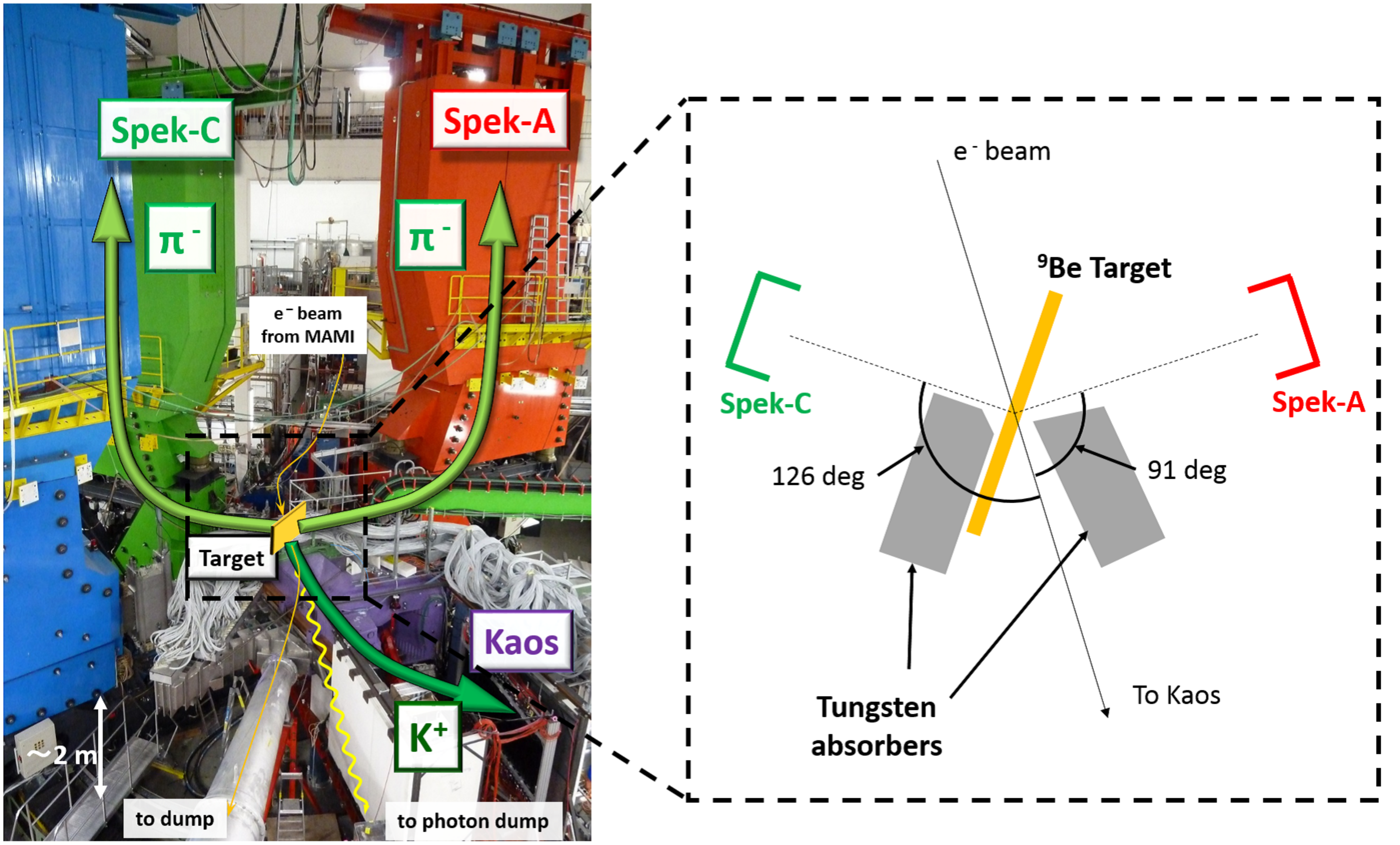
Mainzer-Microtron: MAMI

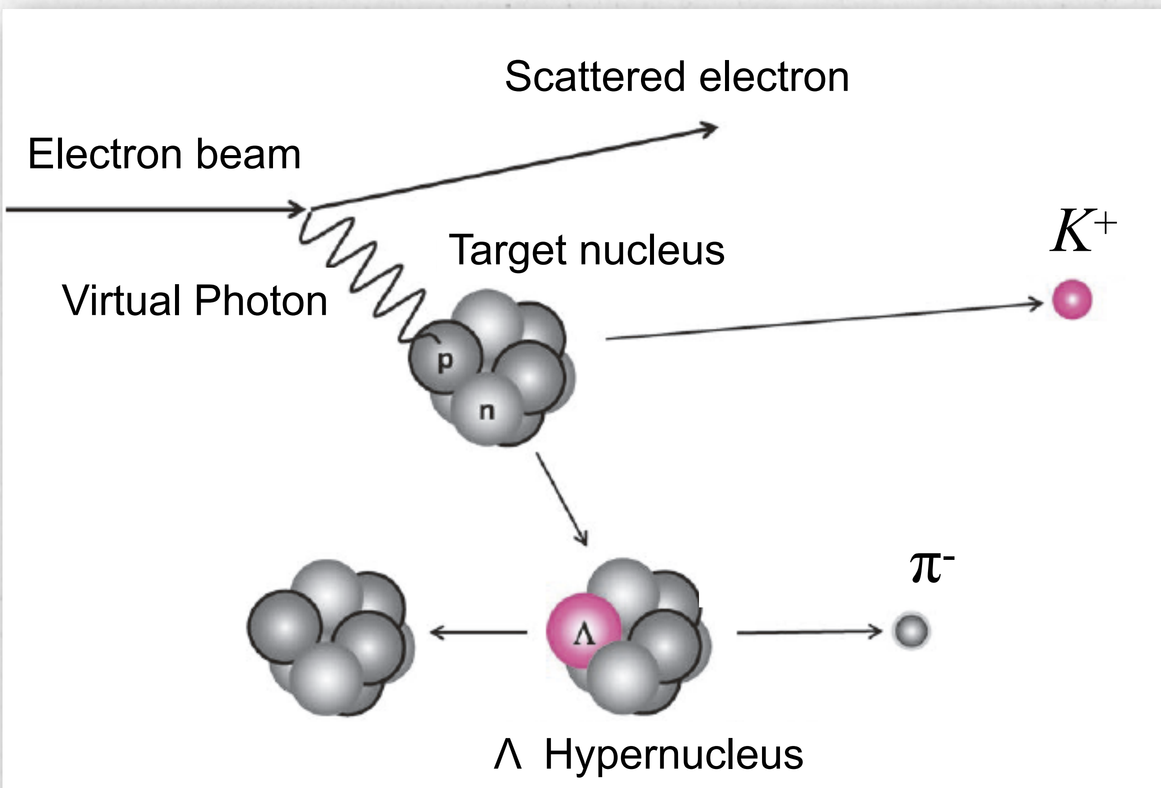


Detector system and optical properties will be found in
http://wwwa1.kph.uni-mainz.de/A1/detector.html
http://wwwa1.kph.uni-mainz.de/A1/magnet.html

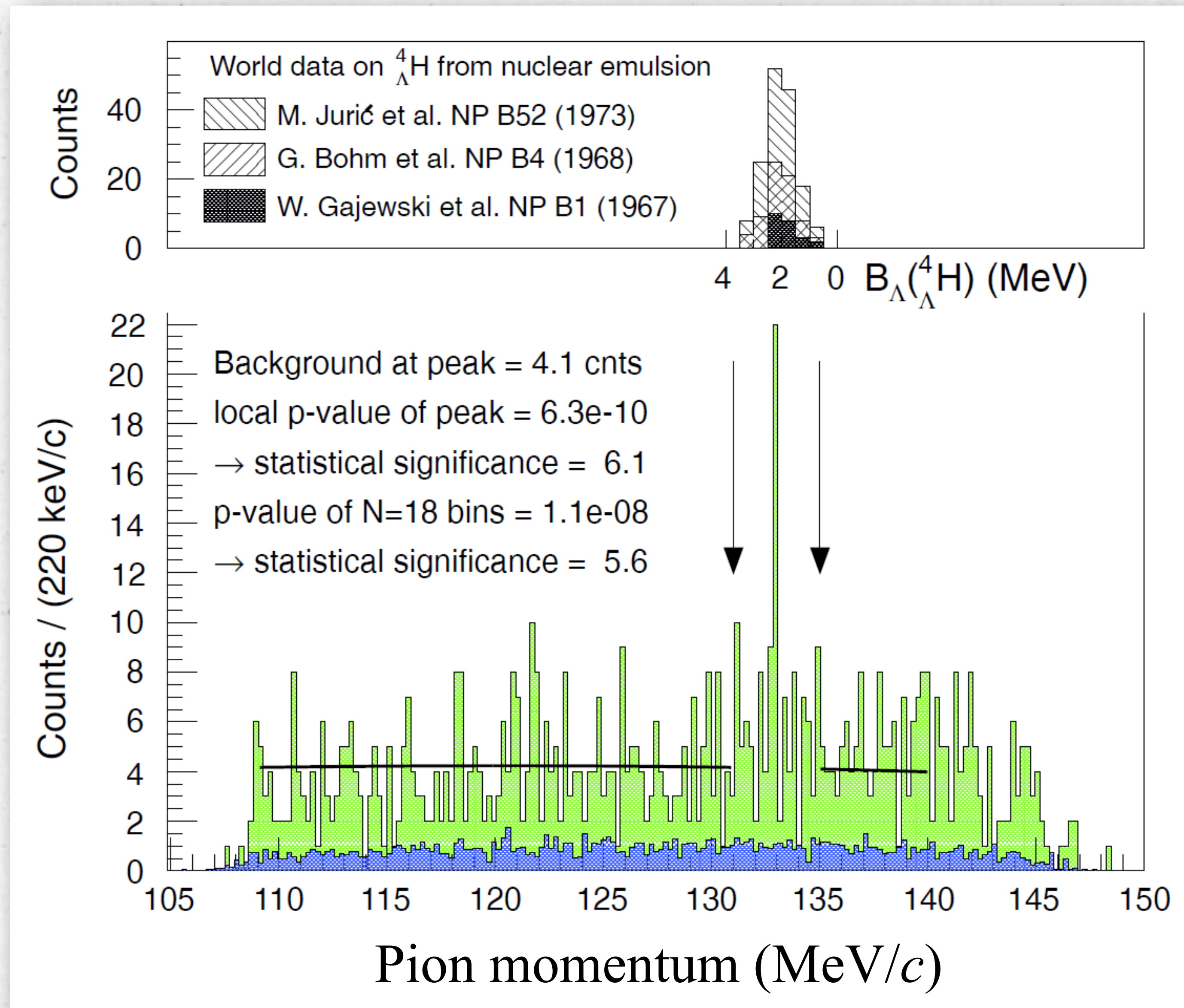
Setup at A1 Hall



Result from MAMI



A.Esser, S.Nagao et al. PRL 114 (2015) 232501



$B_\Lambda = 2.12 \pm 0.01 \pm 0.09$ MeV

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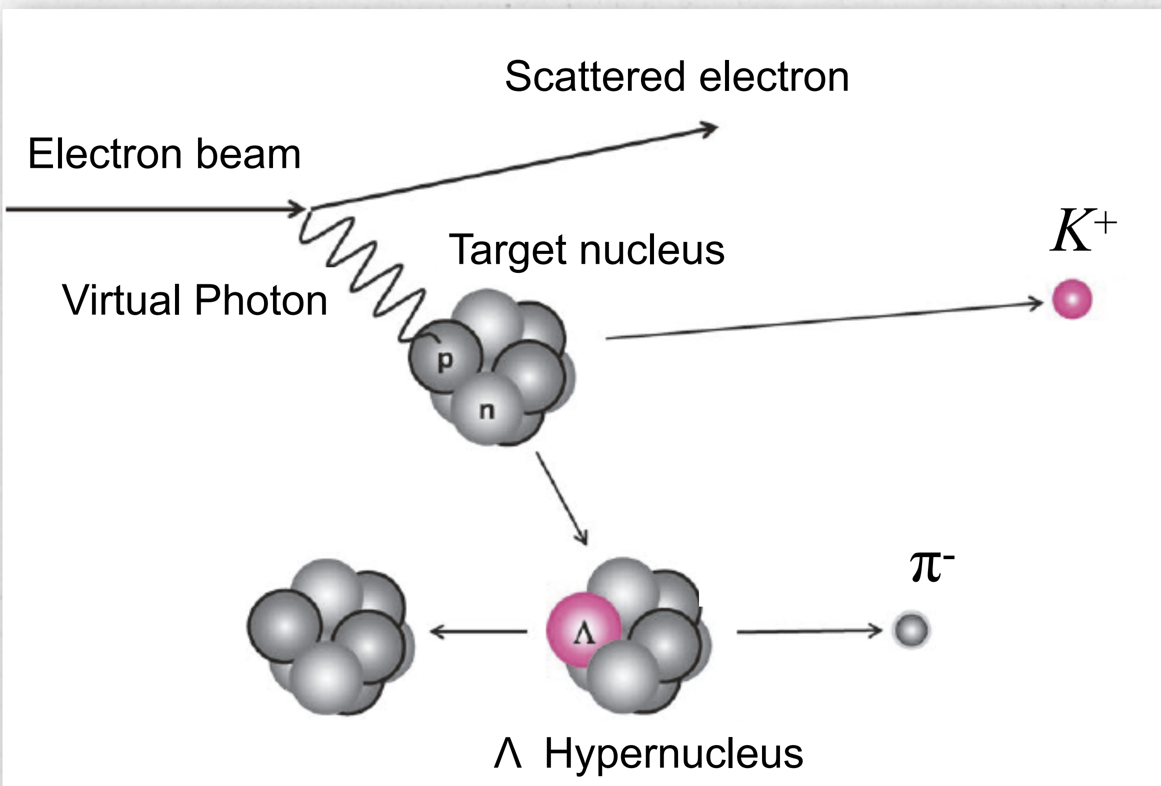

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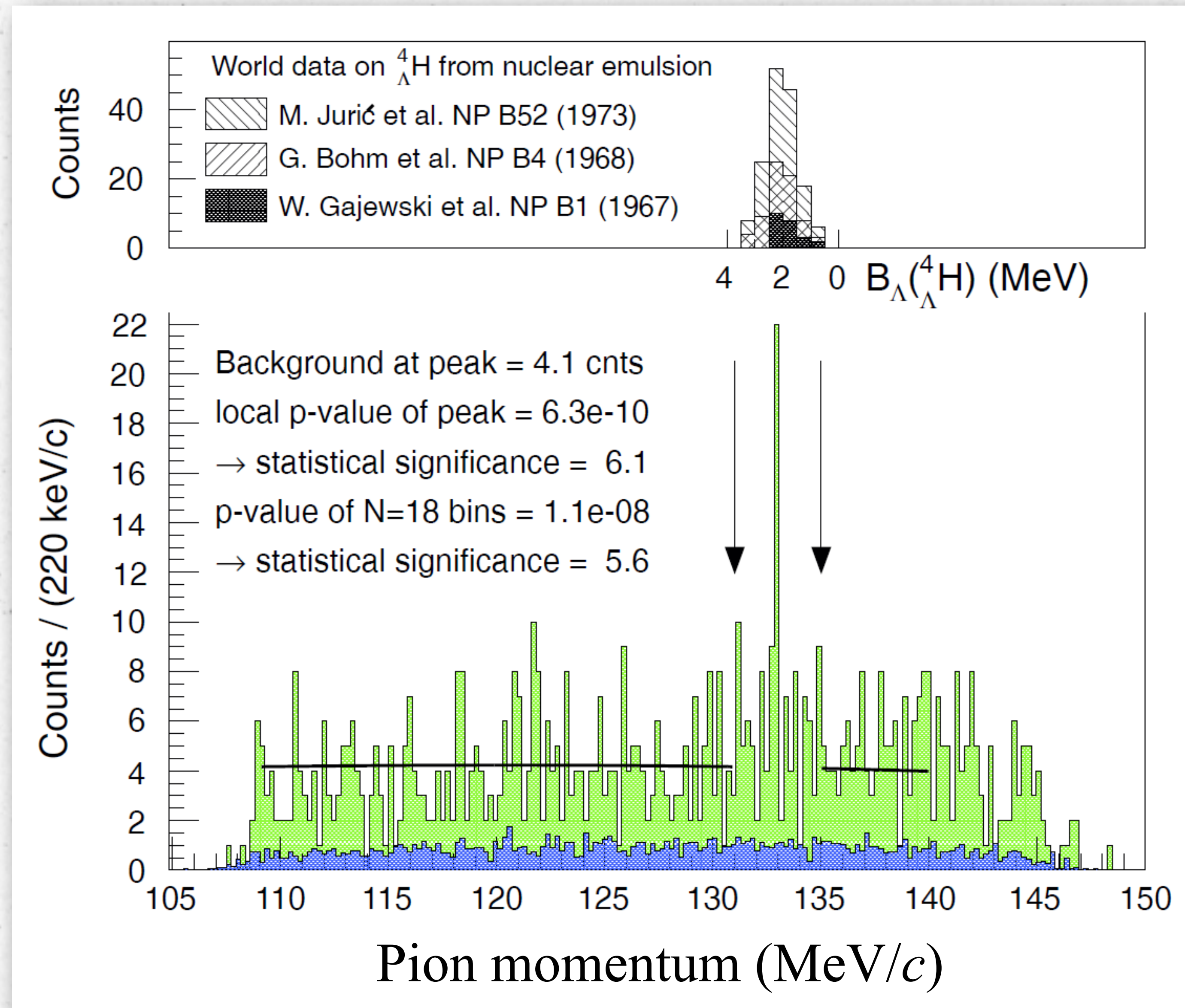

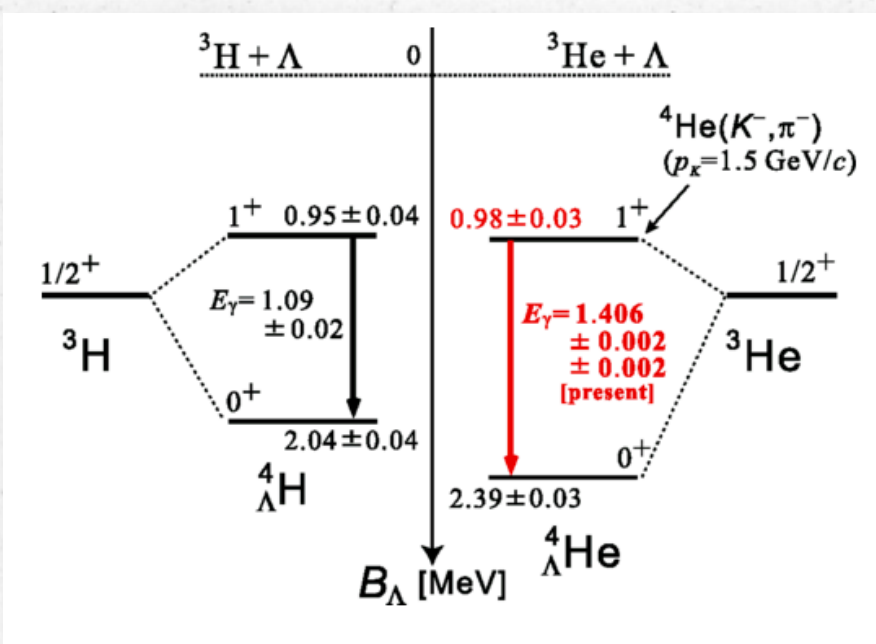

T.O. Yamamoto et al.
PRL 115 (2015) 222501
Note: B_Λ of $^4_\Lambda$H is old value

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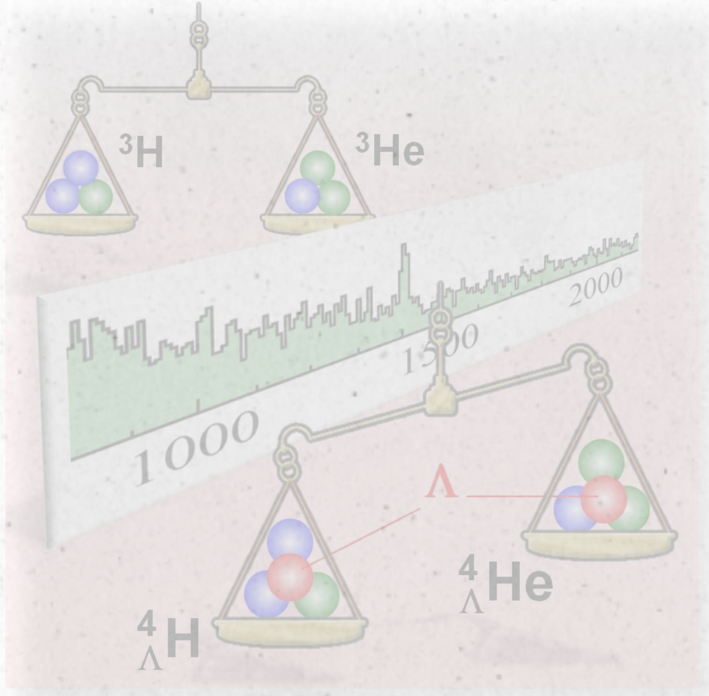

Figure from Prof. Tamura

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Data of Λp

- Λp scattering

$$K^- + p \to \Lambda + \pi^0, \qquad K^- + p \to \Sigma^- + \pi^+$$

$$K^- + p \to \Sigma^0 + \pi^0, \quad \Sigma^0 \to \Lambda + \gamma, \qquad \Sigma^- + p \to \Lambda + n,$$

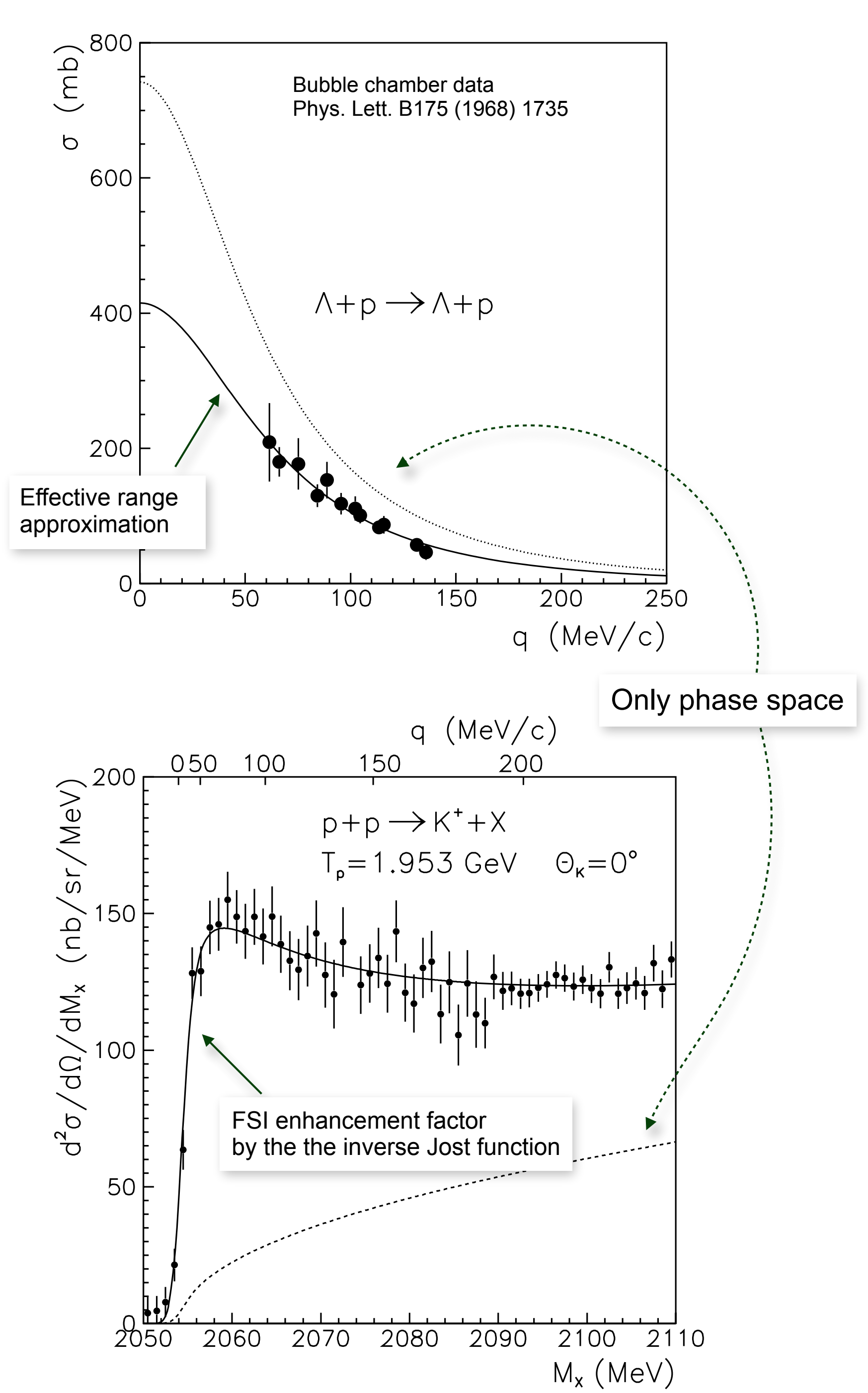
$$\Sigma^- + p \to \Sigma^0 + n, \quad \Sigma^0 \to \Lambda + \gamma$$

- Λp FSI effect in hadron production

$$K^- + d \to \pi^- + (\Lambda p)$$

$$\pi^+ + d \to K^+ + (\Lambda p)$$

$$p + p \to K^+ + (\Lambda p)$$



Figures from
Phys. Lett. B687 (2010) 31, HIRES collaboration

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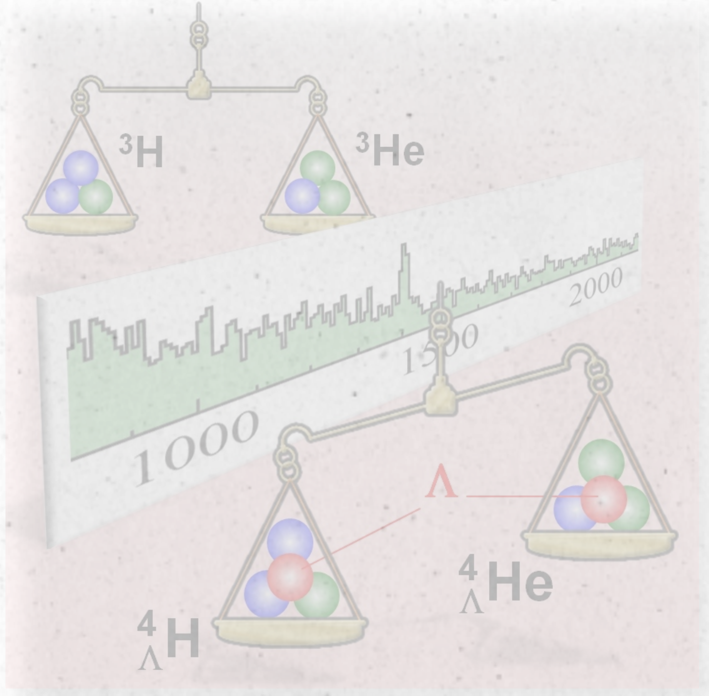

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How to Measure An Interaction

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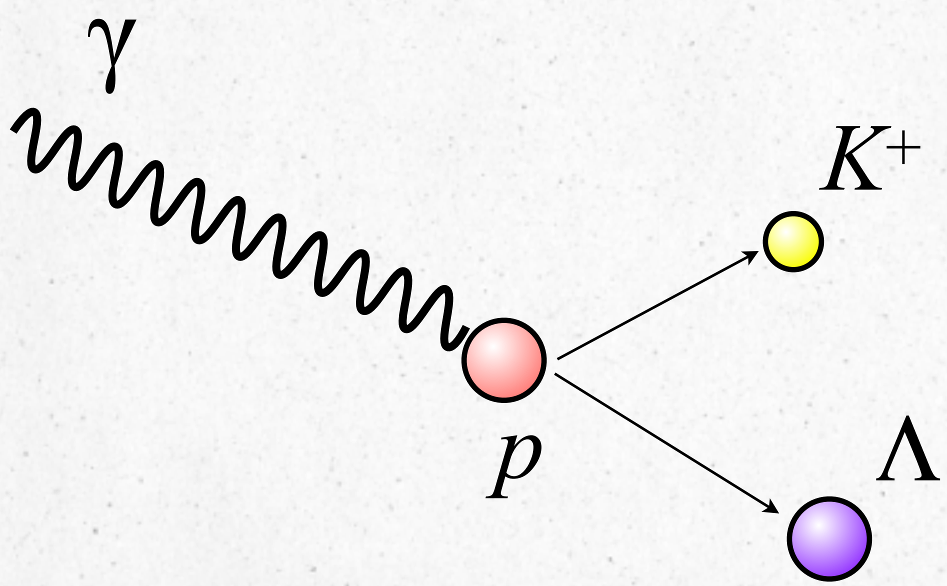

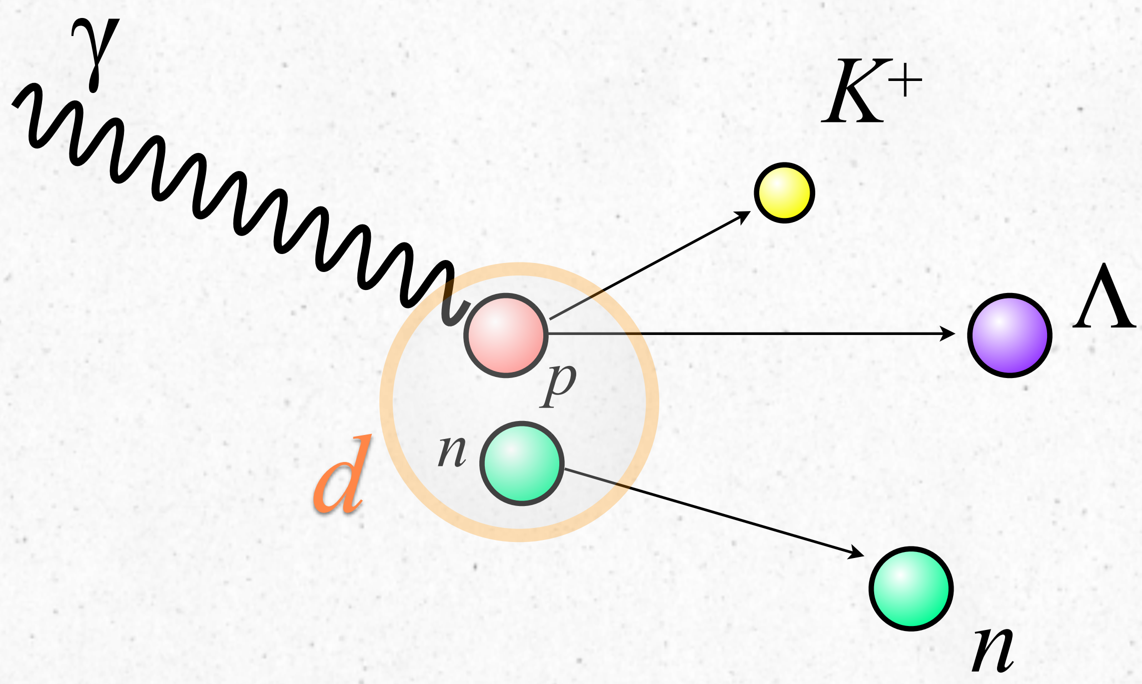

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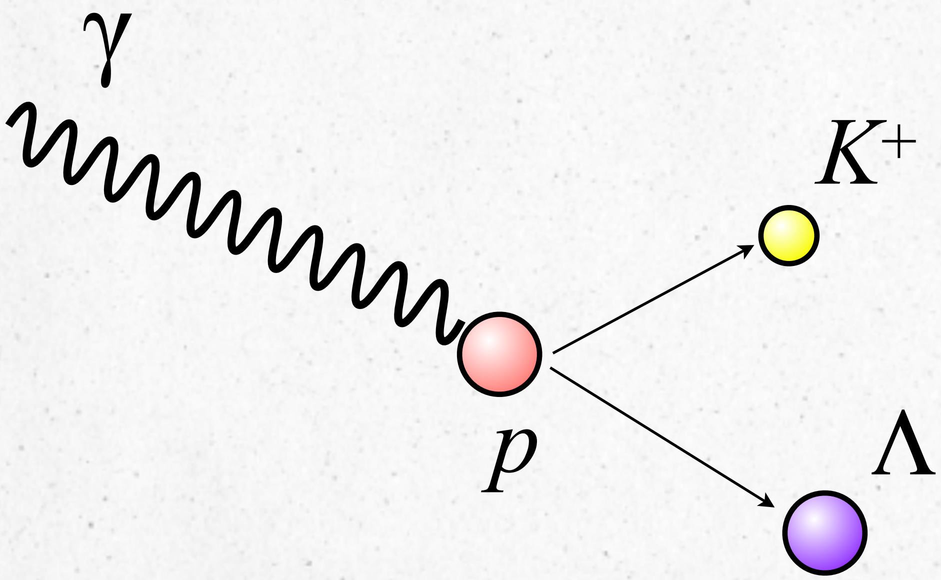

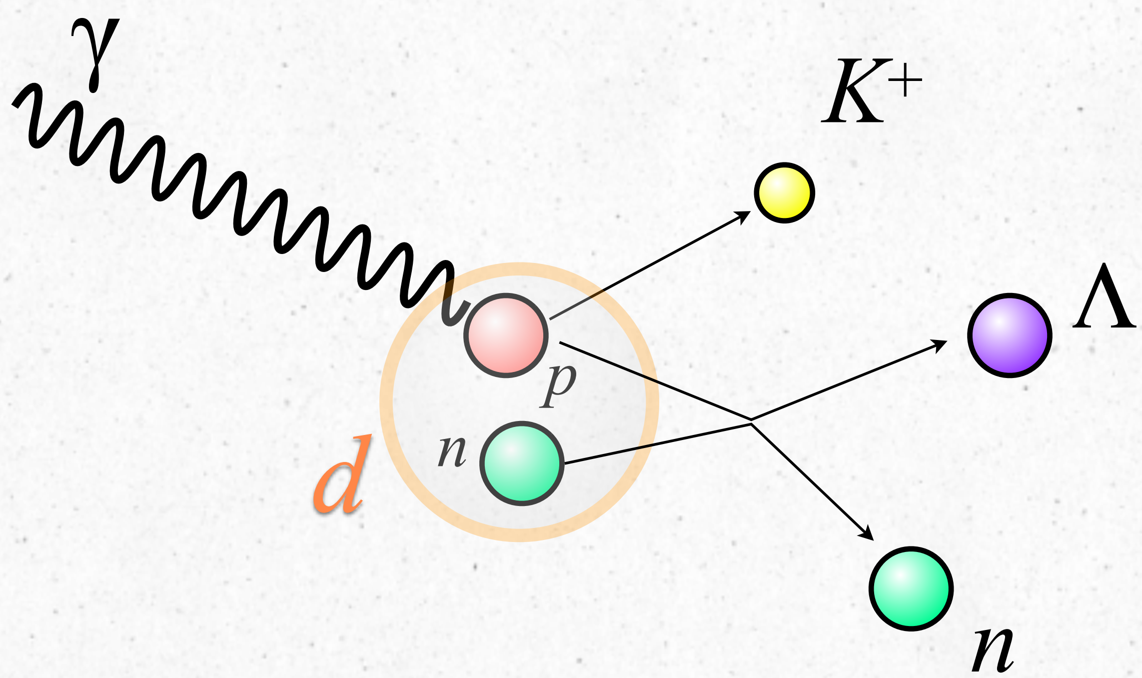

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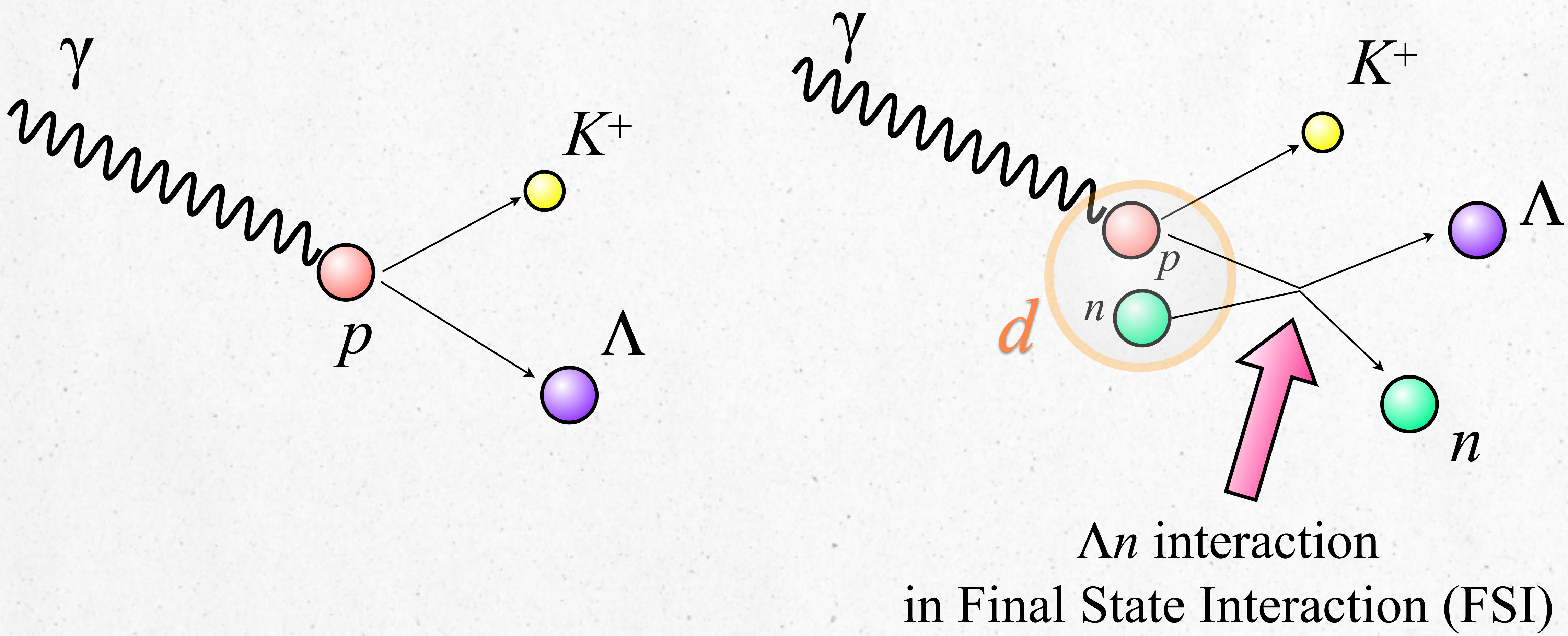

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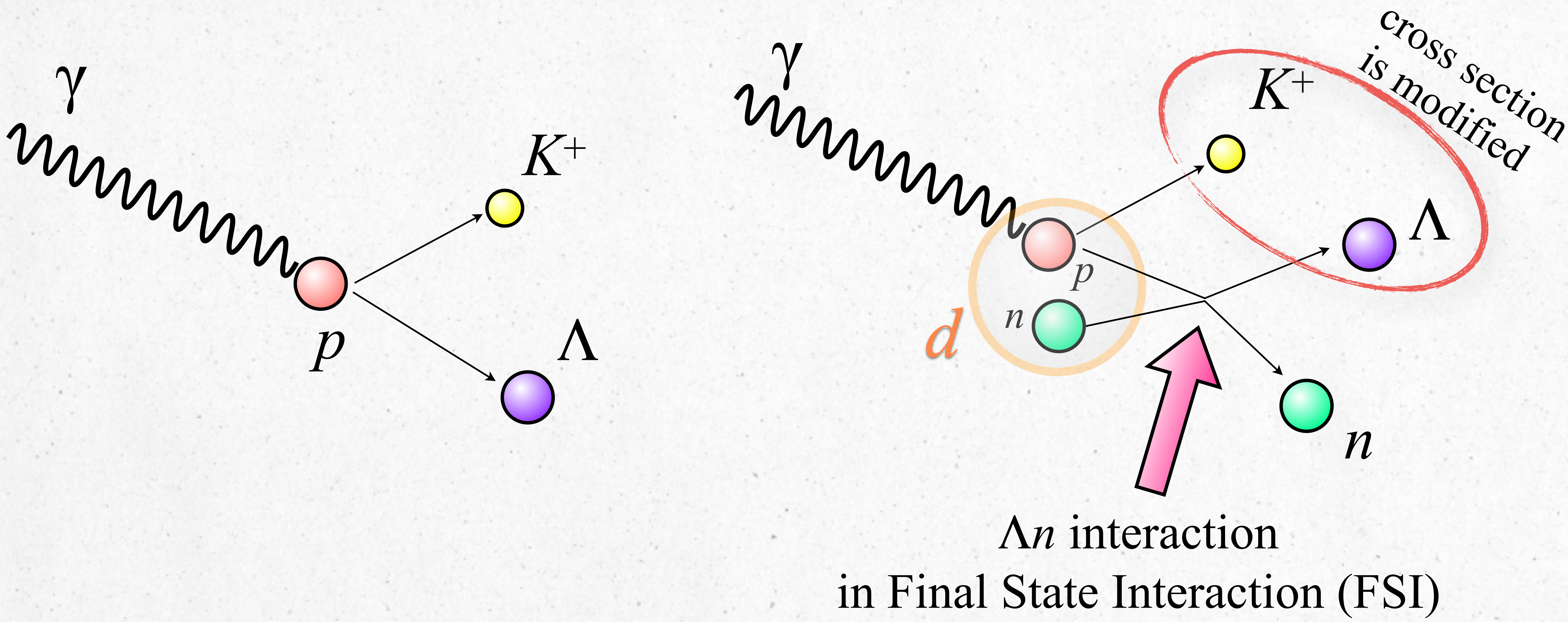

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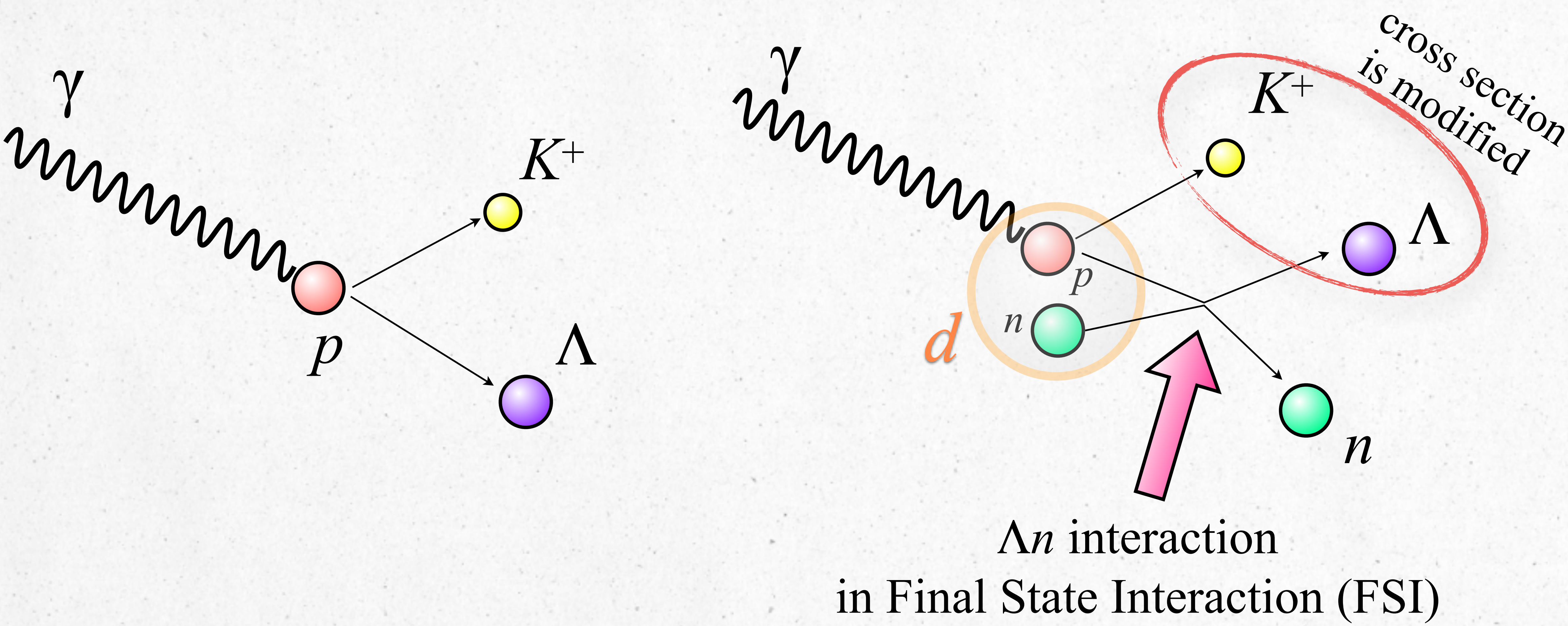
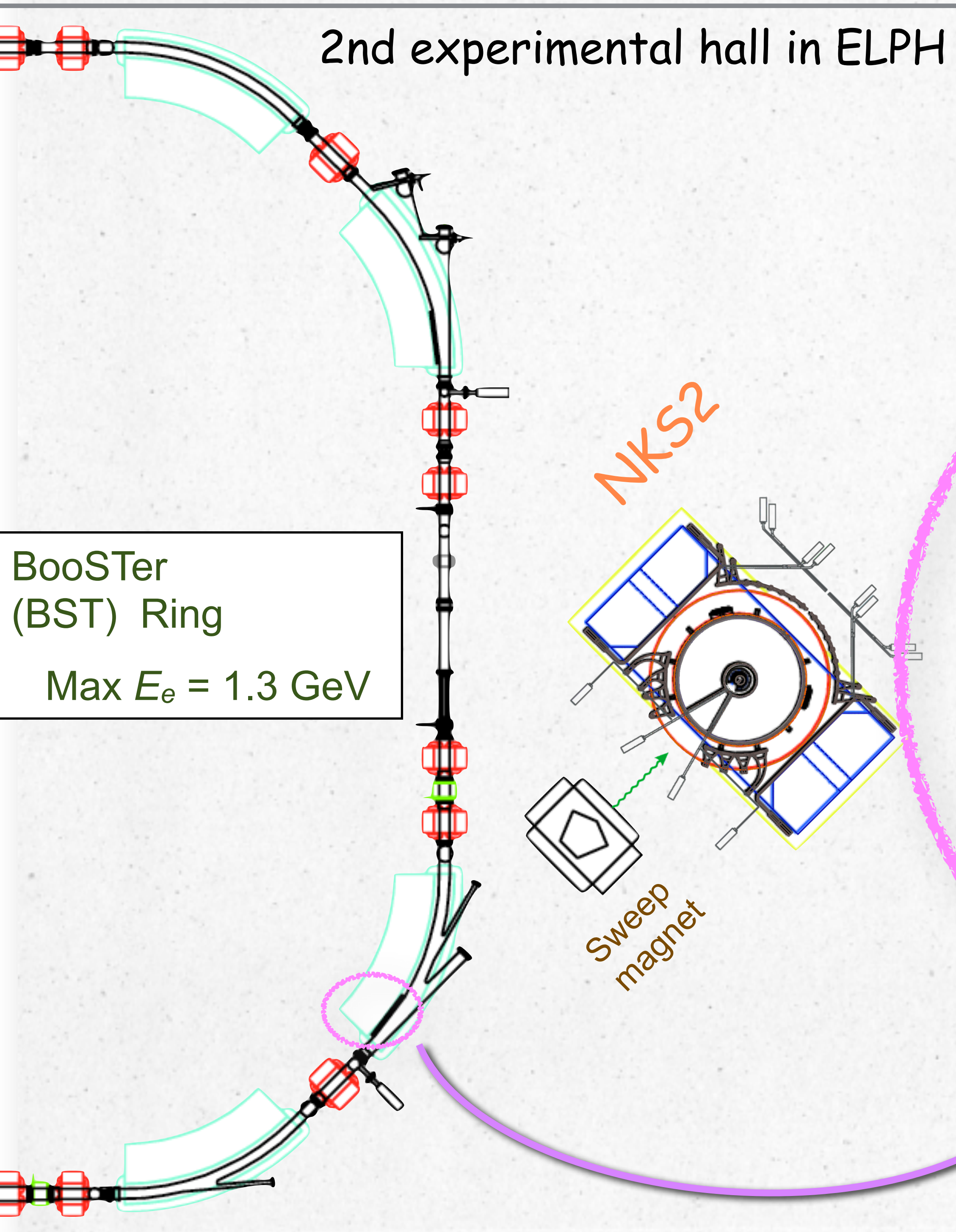


- Using a large acceptance magnetic spectrometer

Our Experiment:
NKS2
at ELPH, Tohoku Univ.

Photon Beam Line

in Research Center of Electron Photon Science (ELPH), Tohoku Univ.

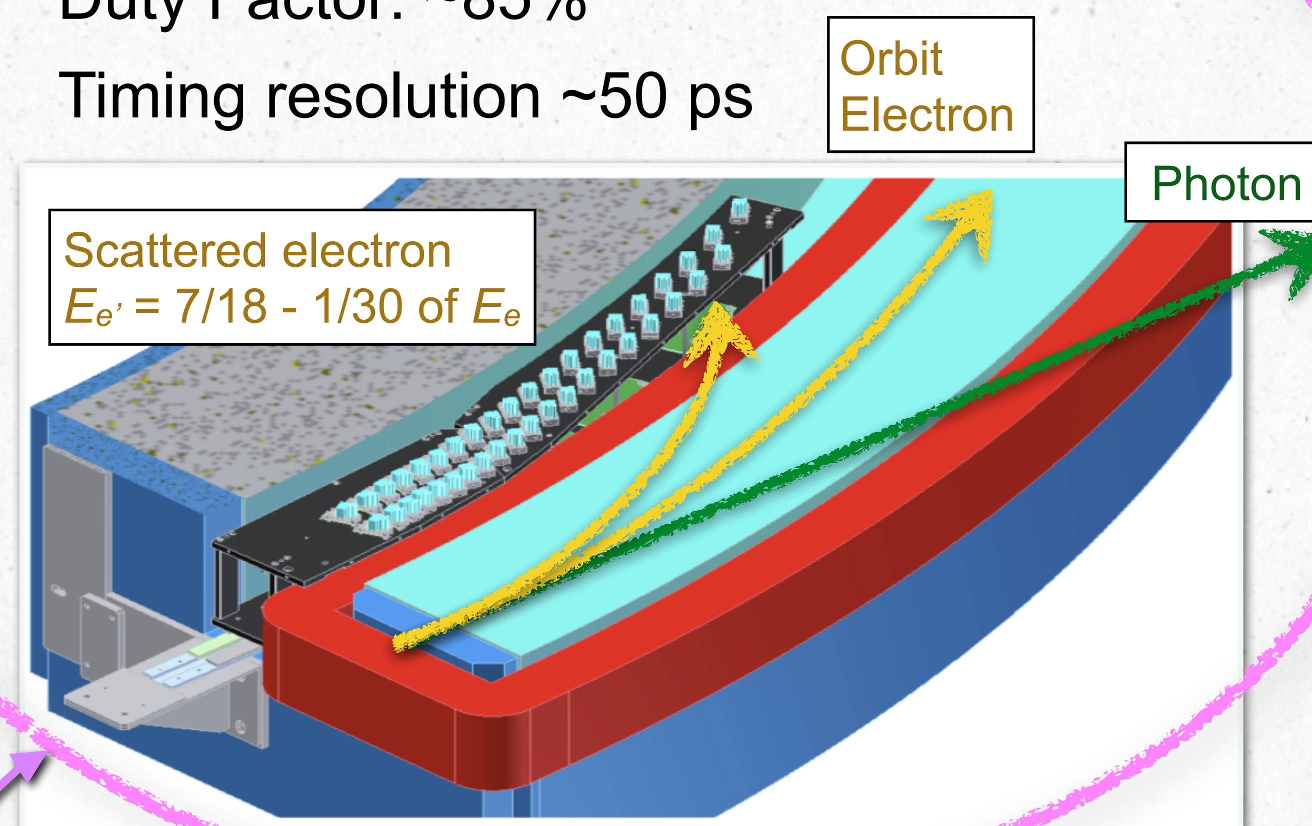


See IEEE Transactions on Nuclear Science 61 (2014) 1278, T. Nishizawa et al. for Tagging counter in detail

Tagged Photon Rate: 1-3 MHz

Duty Factor: ~85%

Timing resolution ~50 ps



The NKS2 Experiment

- Tagged photon beam
  - E_γ = 0.80-1.25 GeV
- Liquid D_2 or H_2 target
- Magnetic spectrometer
  - Tracker
    - Two drift chambers
    - Charged particle momentum, trajectory, and decay vertex
  - Hodoscopes
    - Plastic scintillator + PMT
    - Time-Of-Flight (TOF)
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  - Electron Veto
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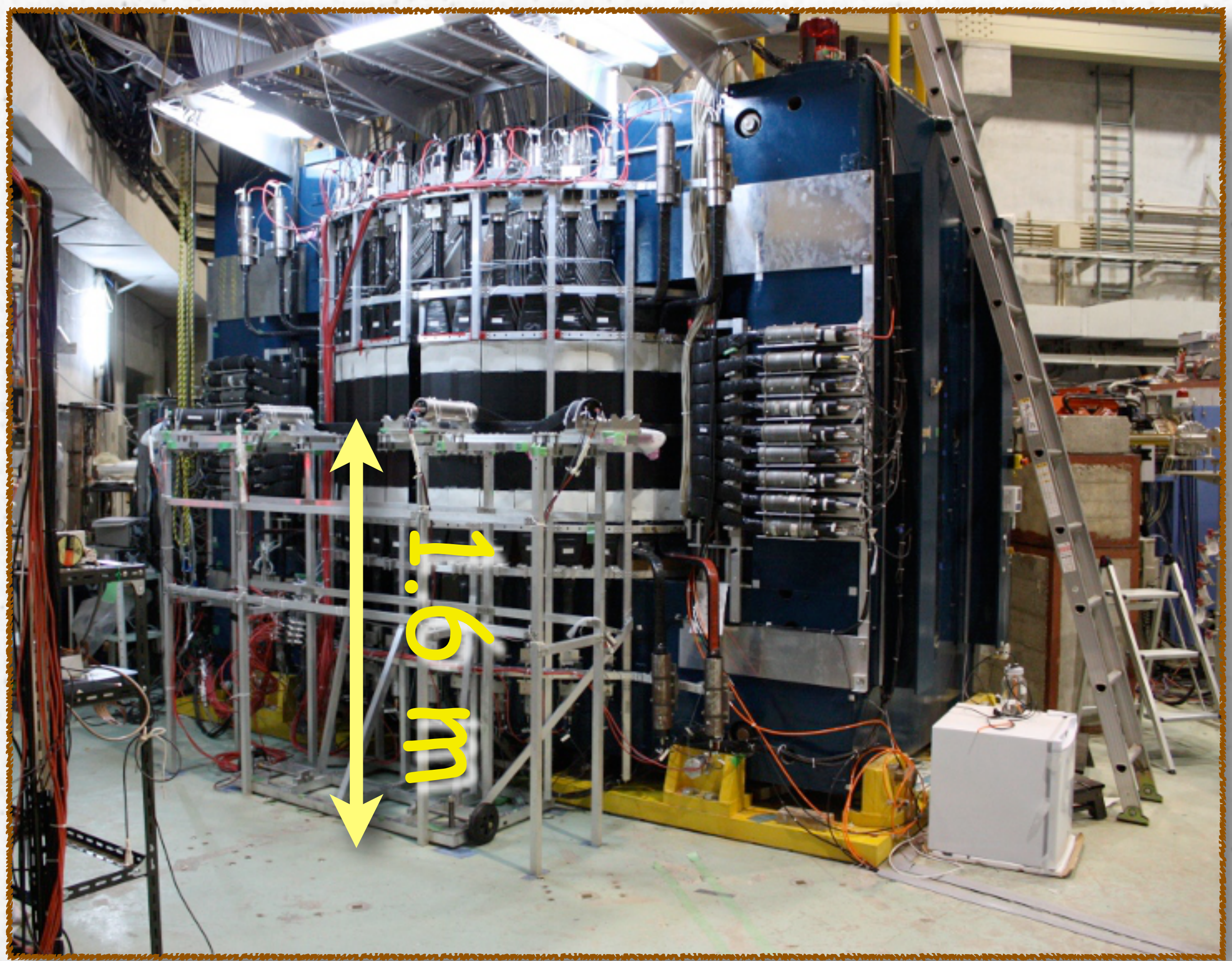
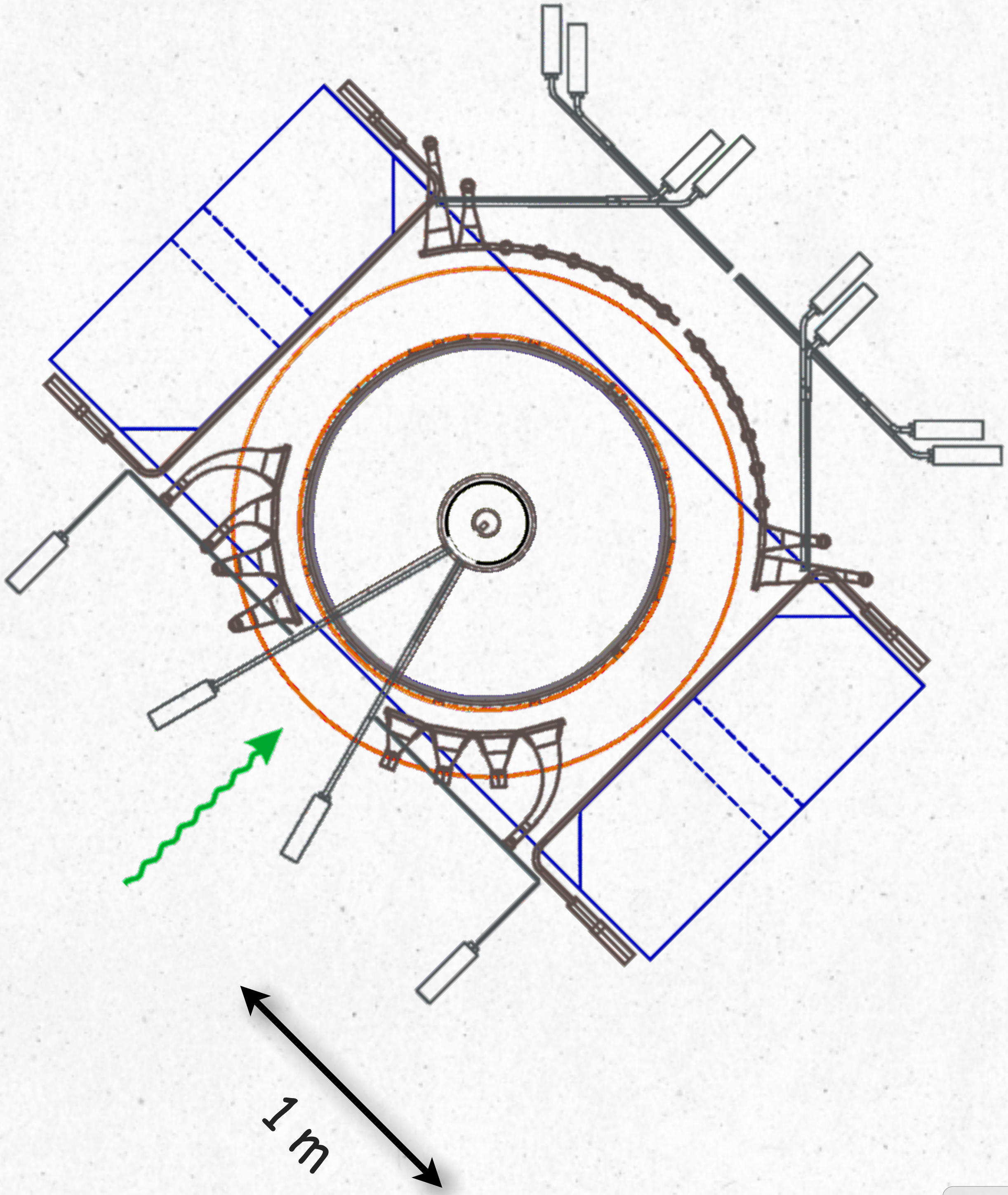
  - Covering large kinematic region including forward angle





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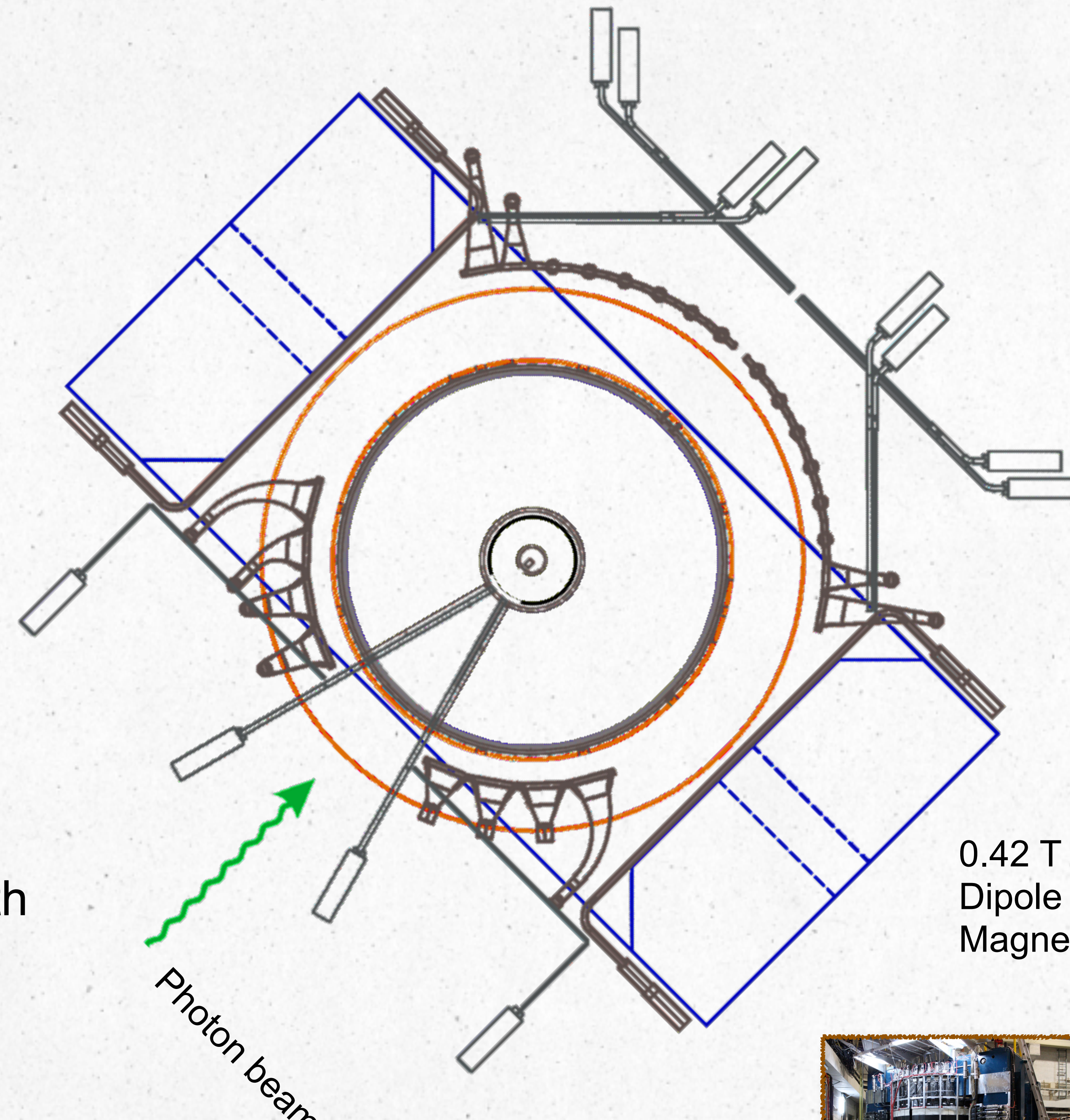

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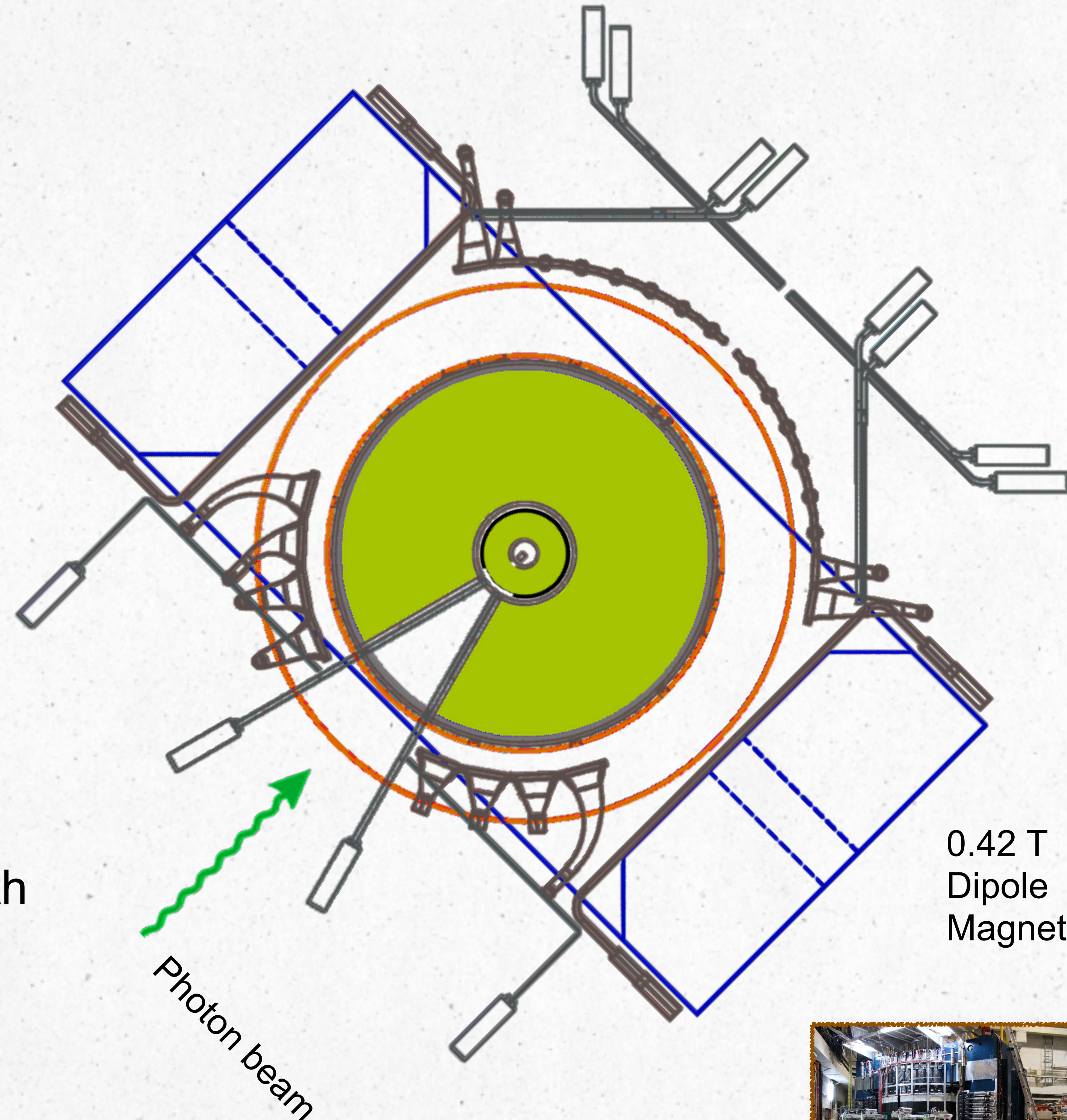

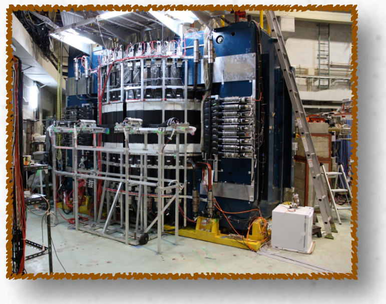

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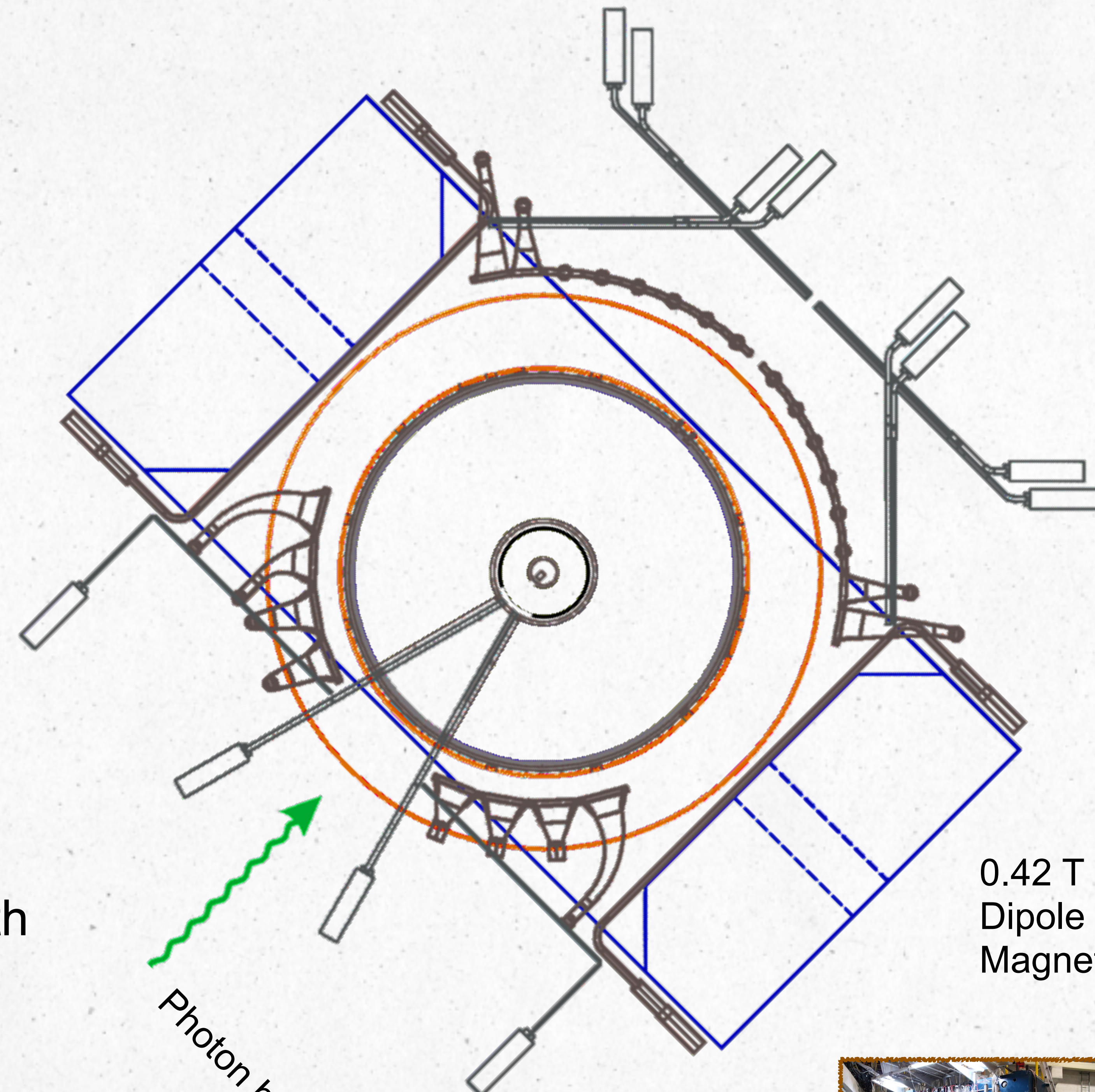

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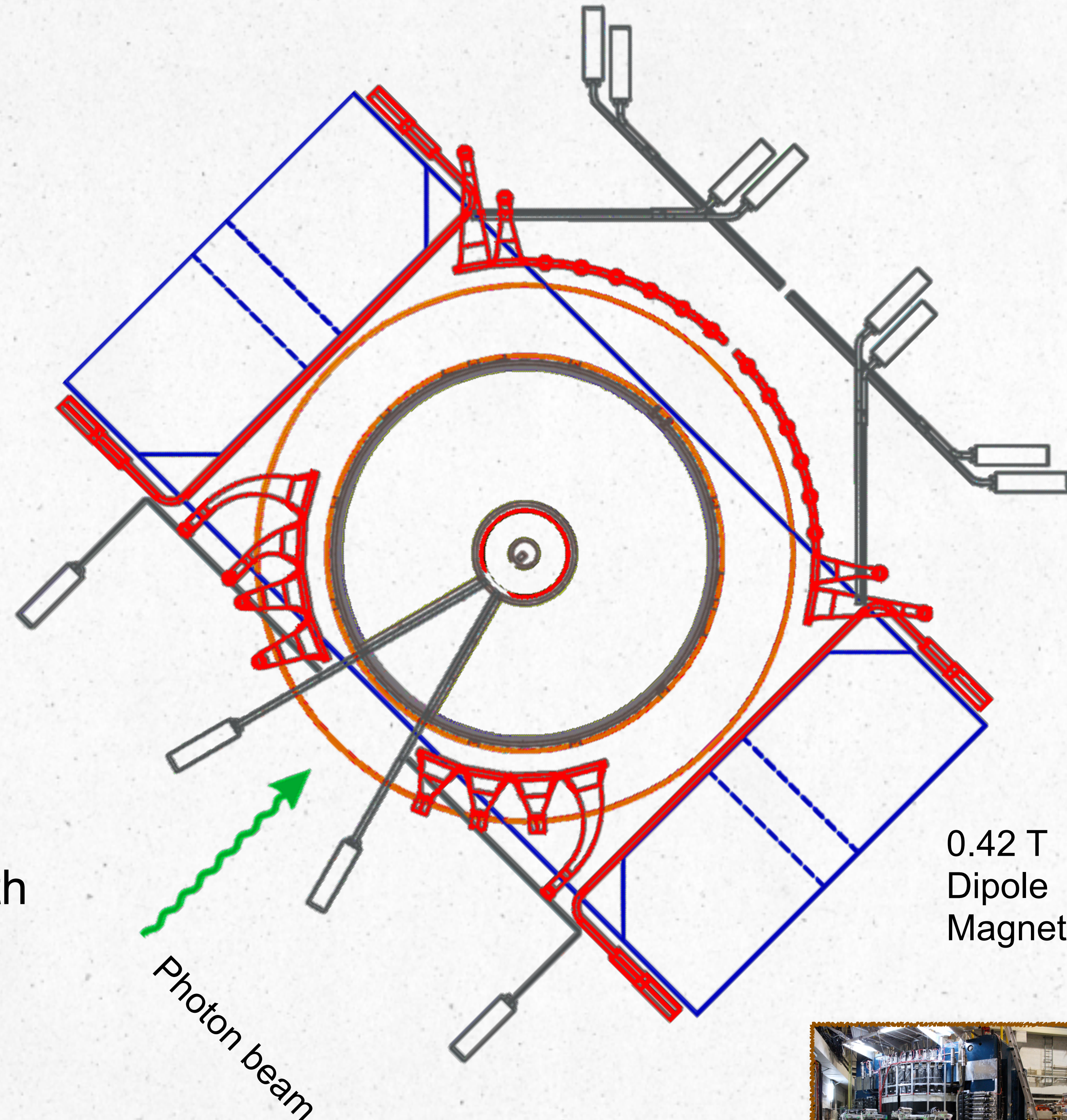

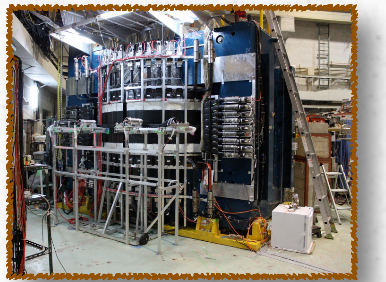

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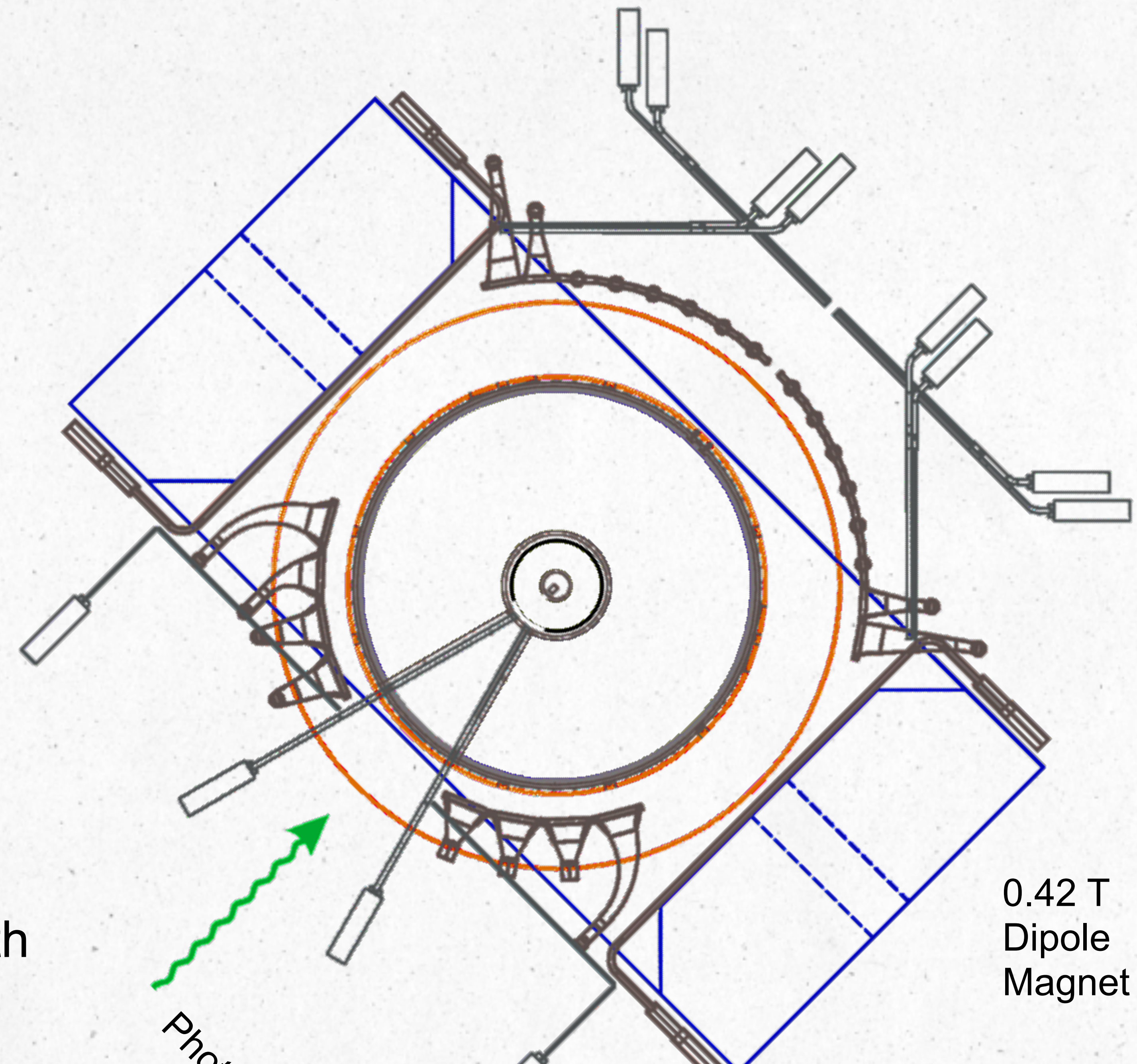

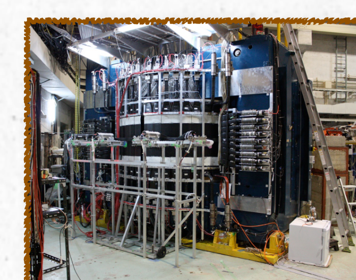

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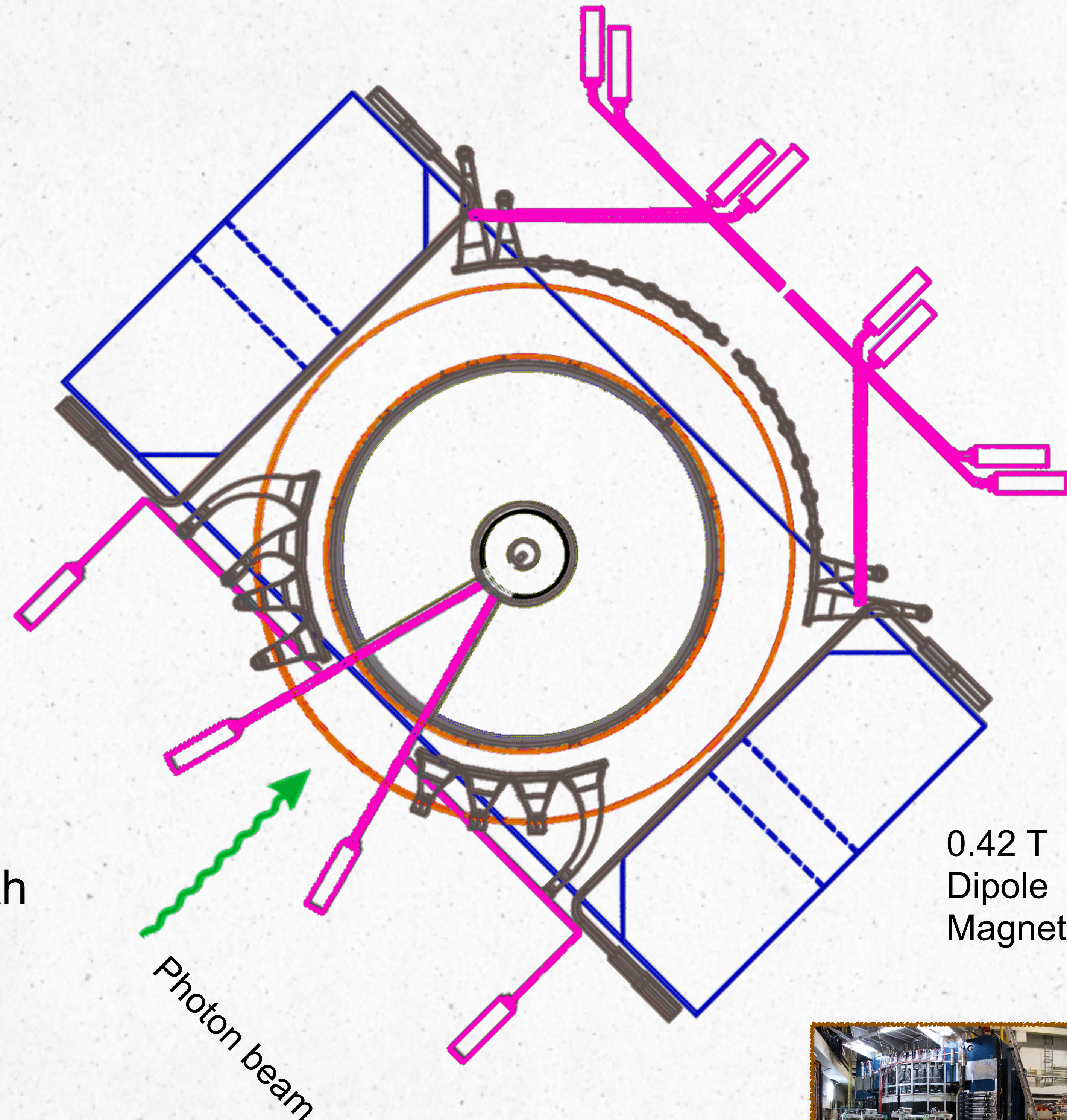

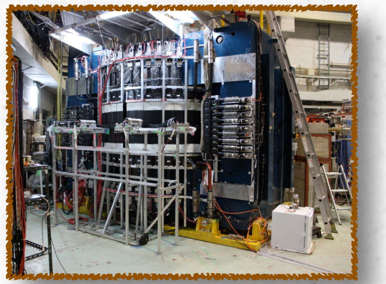

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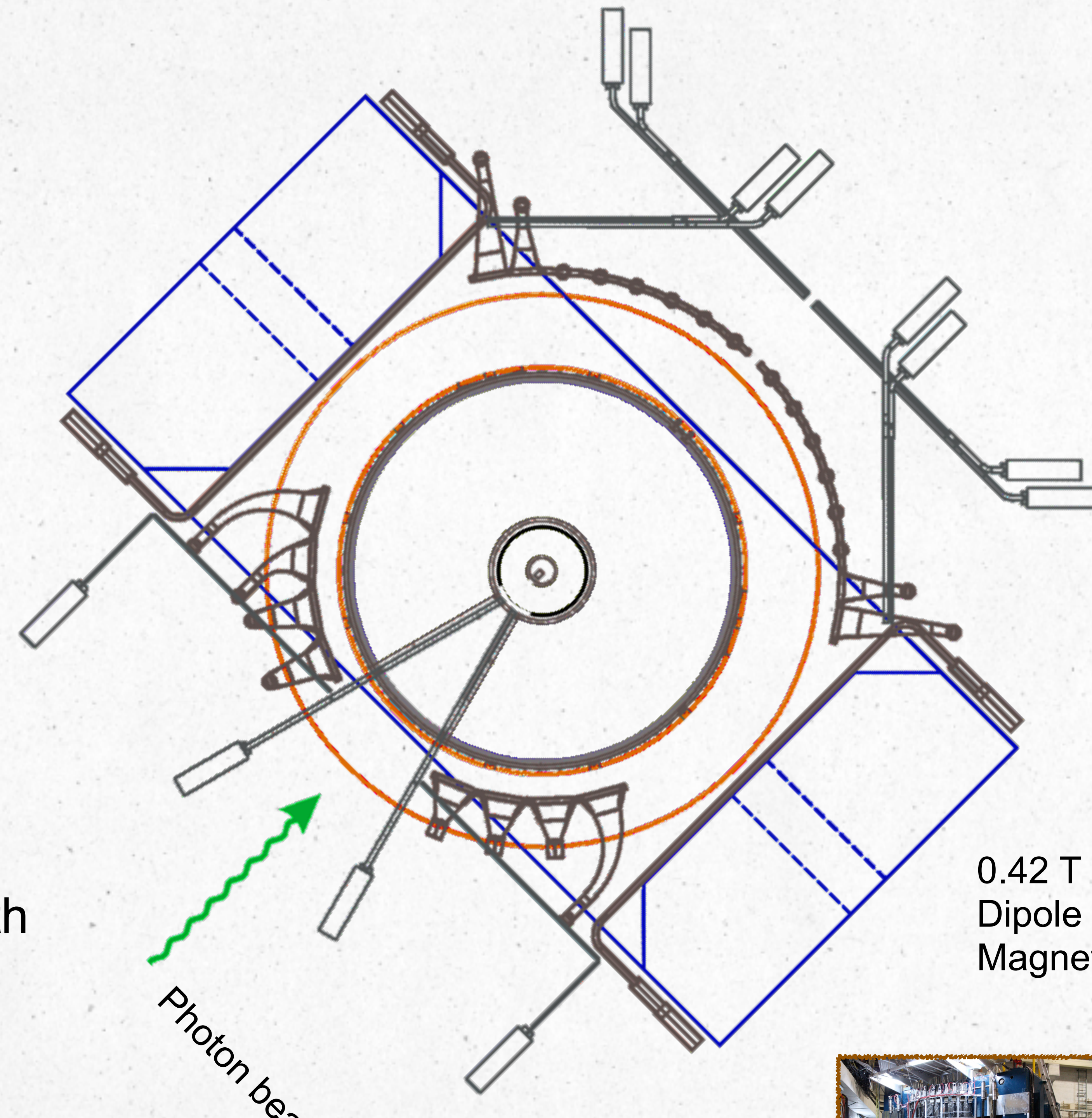
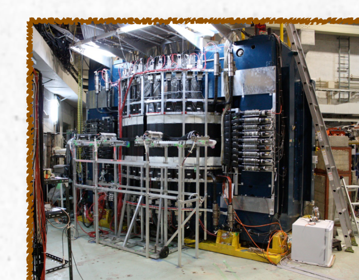




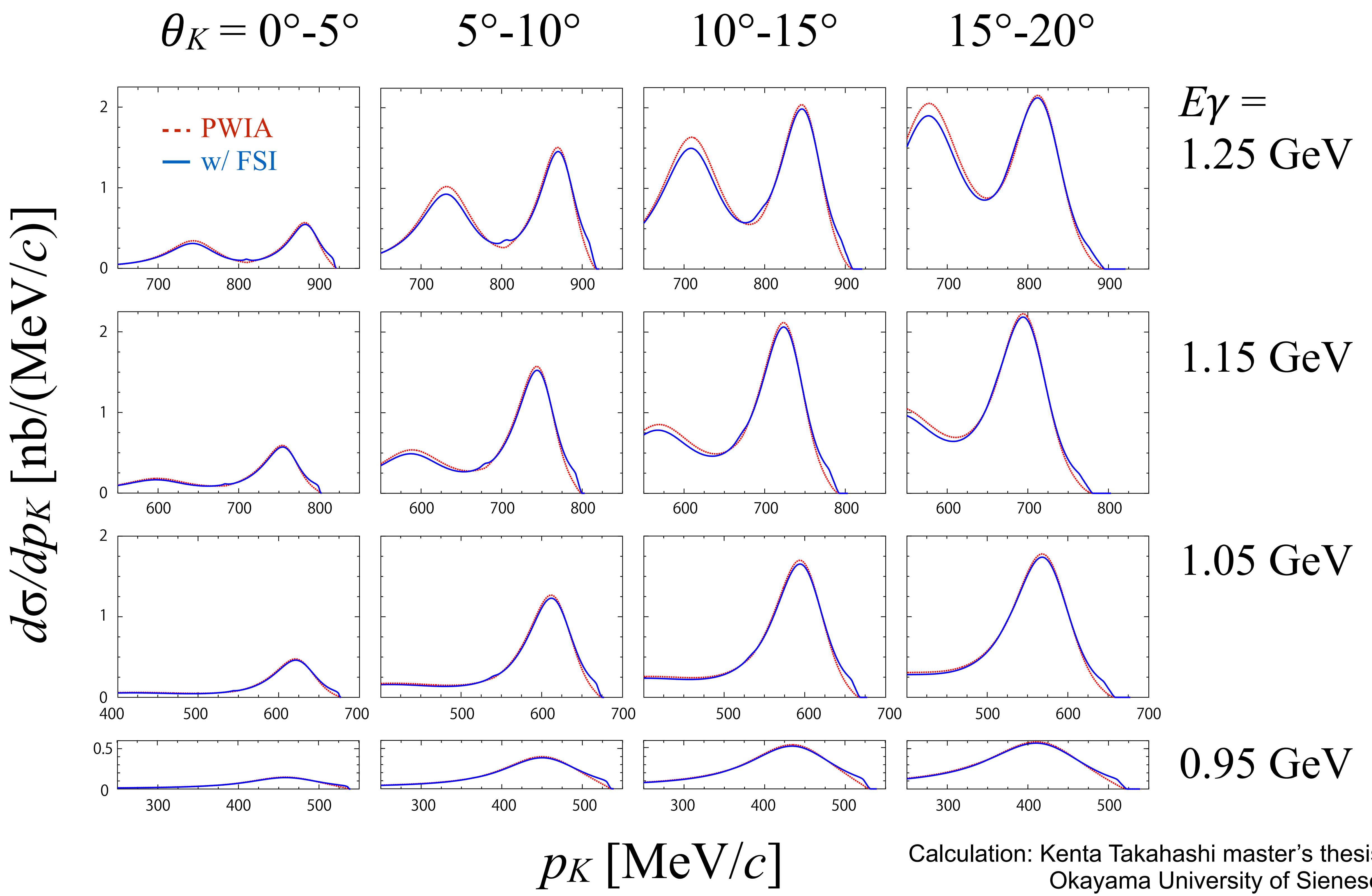
An Interaction Study by NKS2

FSI seen in JLab

FSI Effect: How looks like in NKS2?

- Calculation
  - by K. Takahashi of Miyagawa-san's group in Okayama University of Science
    - K+ cross-section in $\gamma d \rightarrow K^{+}\Lambda n$
    - $E\gamma$ = 0.95 - 1.25 GeV
    - $d\sigma/dp_K$ in Lab. frame
    - θ_K = 0°-20°
  - shown in his master's thesis (FY2017)

FSI Effect in the K+ Cross-section



Calculation: Kenta Takahashi master's thesis
Okayama University of Sienese

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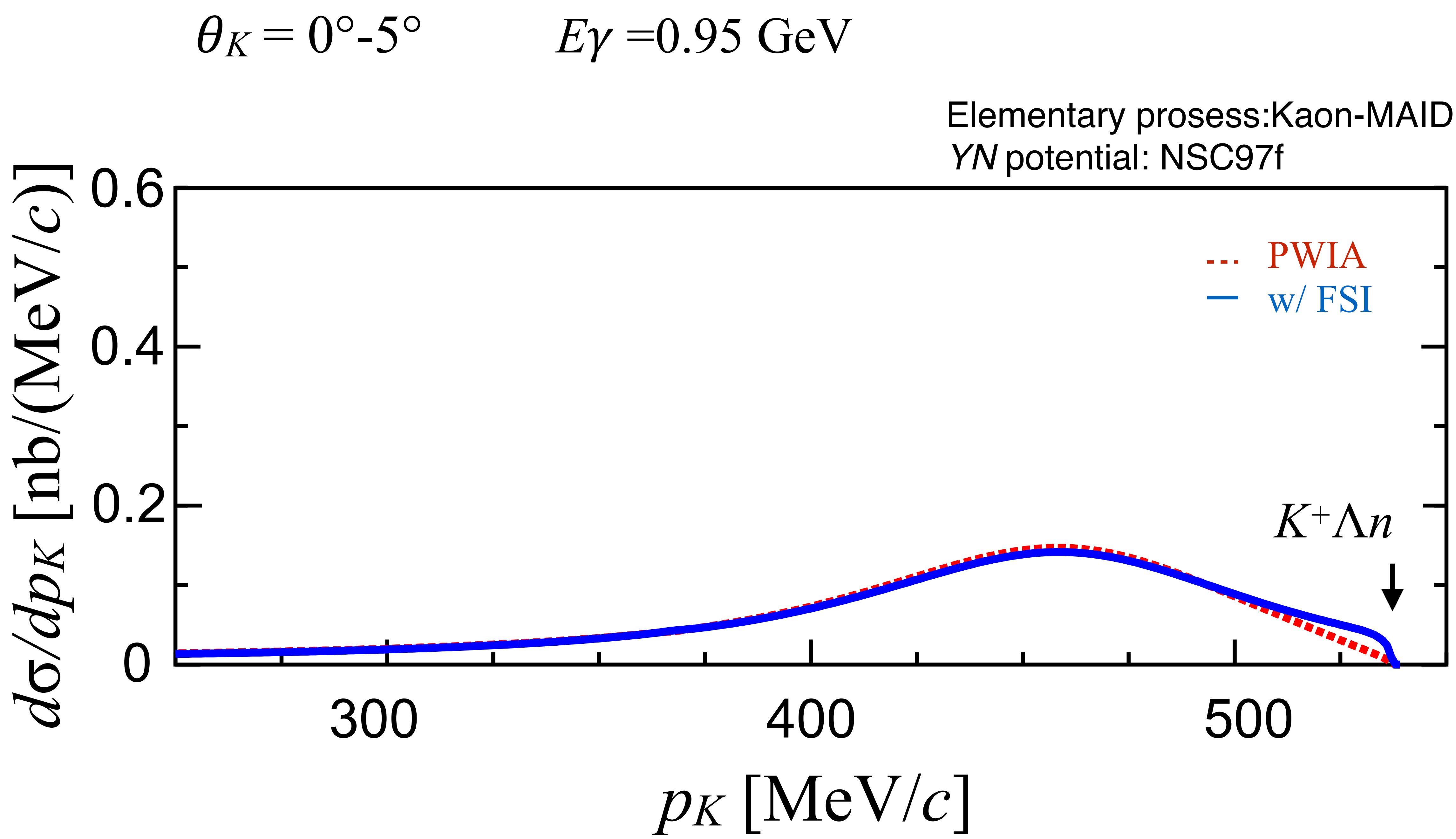

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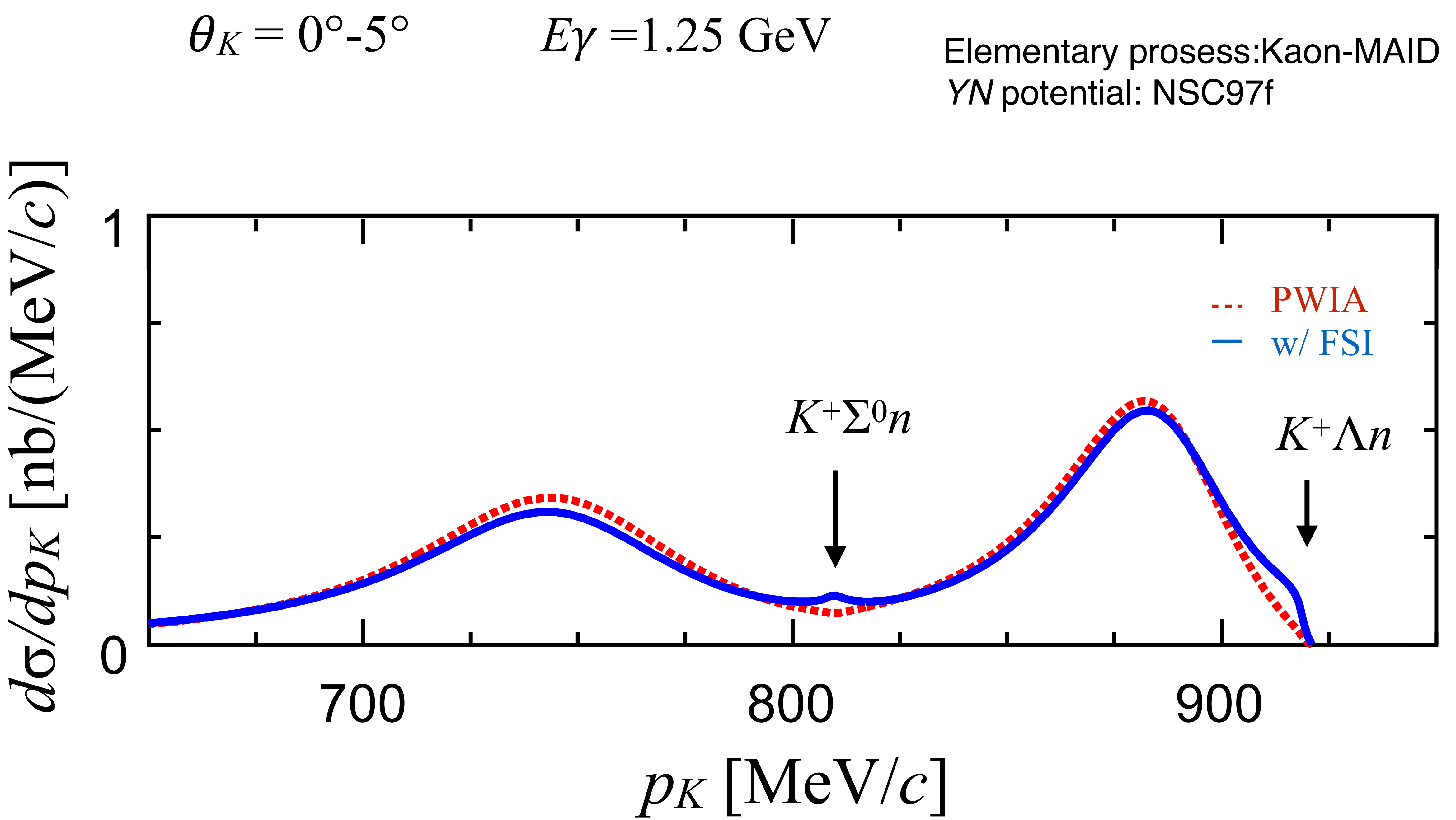
FSI Effect in the K⁺ Cross-section



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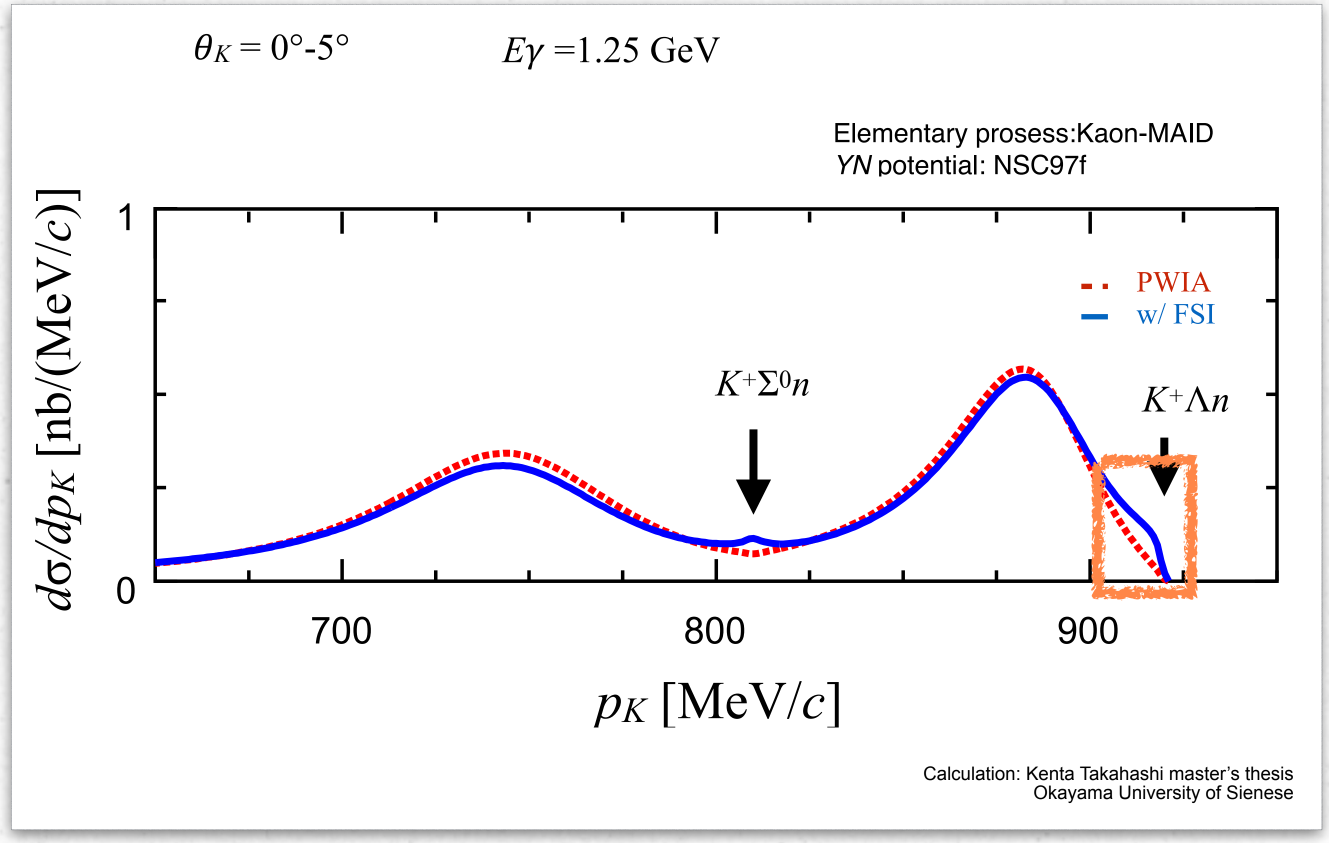
FSI effect in the Cross-section

- The effect appeared near the production threshold
  - Λn
    - ~10 nb in $E\gamma$ > 1.05 GeV
      - summed over θ_K = 0°-20°
      - enhancement seen in ~10 MeV/c momentum range of K^+

FSI effect in the Cross-section

- The effect appeared near the production threshold
  - *Λn*
    - ~10 nb in $E\gamma$ > 1.05 GeV
      - summed over θ_K = 0°-20°
      - enhancement seen in ~10 MeV/c momentum range of K^+



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    - To achieve a few % statistical error of data
      - Assuming the same condition of previous $K^0{}_S$ measurement
      - 200 - 400 days needed to discuss angle dependence
    - Electron veto counter makes the beam time shorter

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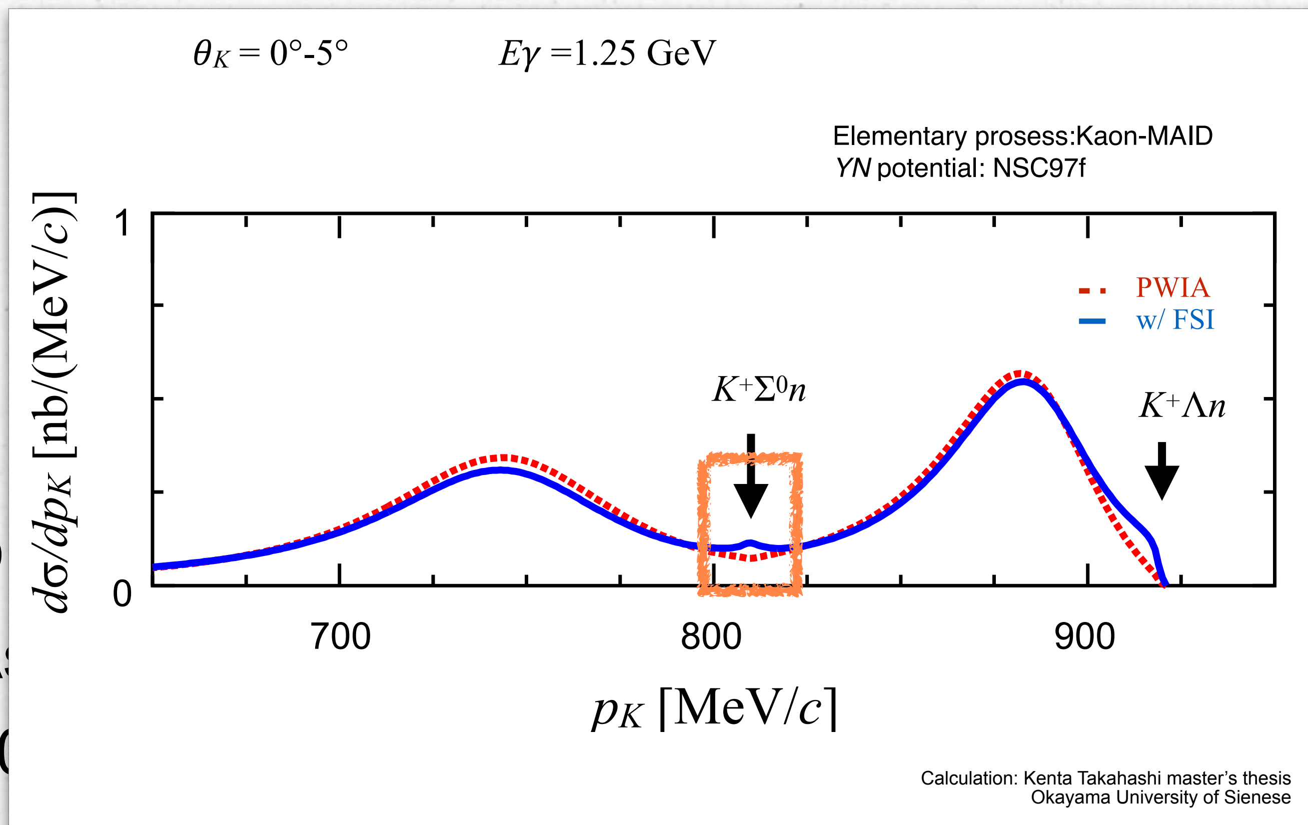
  - Σn
    - "cusp" can be seen in θ_K = 0°-10° and a few nb
      - in $E\gamma \geq$ 1.05 GeV

FSI effect in the Cross-section

- The effect appeared near the production threshold
  - Λn
    - ~1
      -
      - entum range of K^+
    - To
      - As easurement
      - 20 ence
    - Electron veto counter makes the beam time shorter



  - Σn
    - "cusp" can be seen in θ_K = 0°-10° and a few nb
      - in $E\gamma \geq 1.05$ GeV

FSI effect in the Cross-section

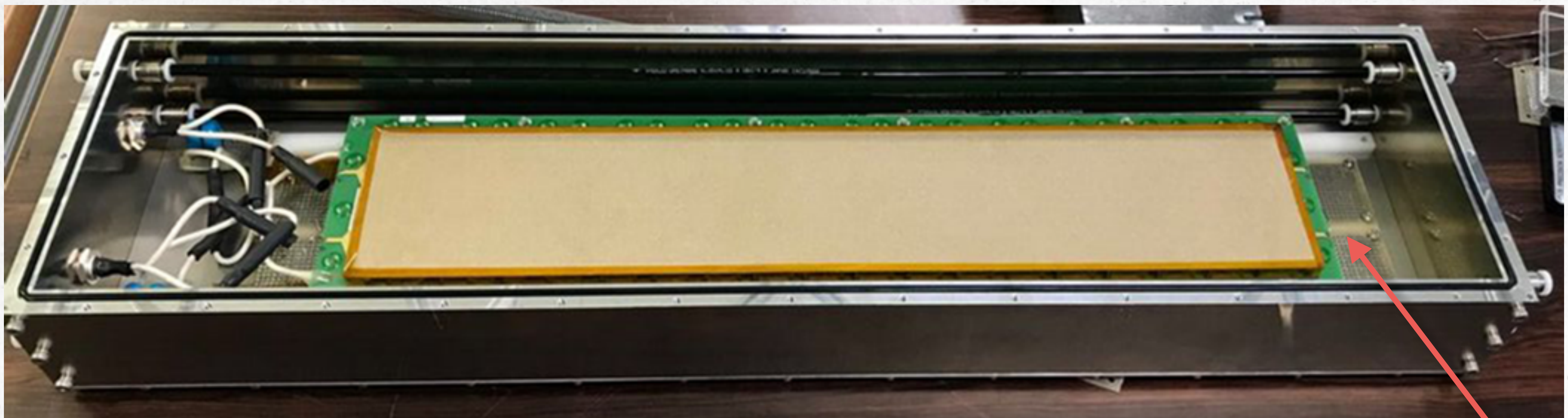
- The effect appeared near the production threshold
  - Λn
    - ~10 nb in $E\gamma$ > 1.05 GeV
      - summed over θ_K = 0°-20°
      - enhancement seen in ~10 MeV/c momentum range of K^+
    - To achieve a few % statistical error of data
      - Assuming the same condition of previous K^0_S measurement
      - 200 - 400 days needed to discuss angle dependence
    - Electron veto counter makes the beam time shorter
  - Σn
    - "cusp" can be seen in θ_K = 0°-10° and a few nb
      - in $E\gamma \geq$ 1.05 GeV

Detector R&D

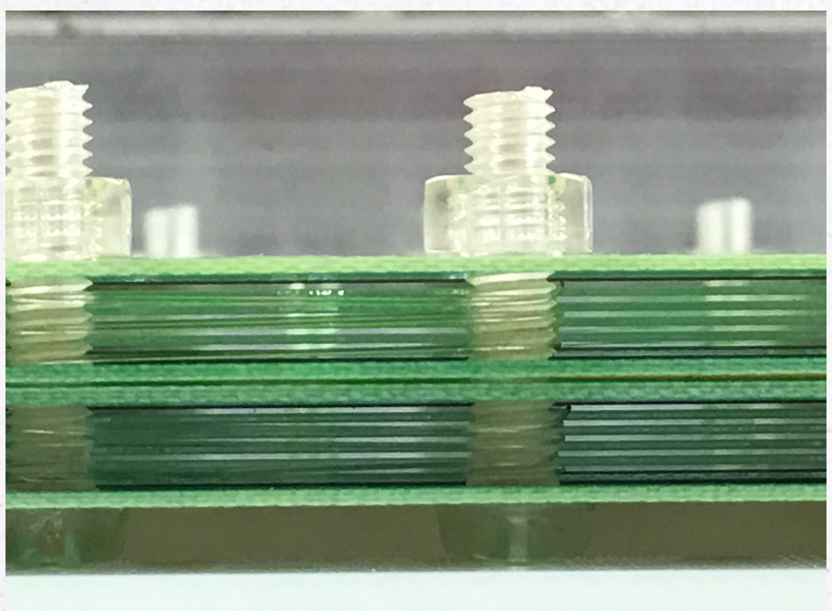
- Multi-gap Resistive Plate Chamber: MRPC
  - Design
    - Gas: R-134a + SF_6 (90:10)
    - 5-gap and double stack
  - Pre-AMP
    - locate closed to MRPC
    - including impedance matching

- Aerogel Cherenkov Counter for Electron Veto
  - Design
    - n=1.01 for e/π separation (π threshold: p = 1 GeV/c)
    - MPPC readout
  - R&D is started

Multi-gap Resistive Plate Chamber (MRPC)

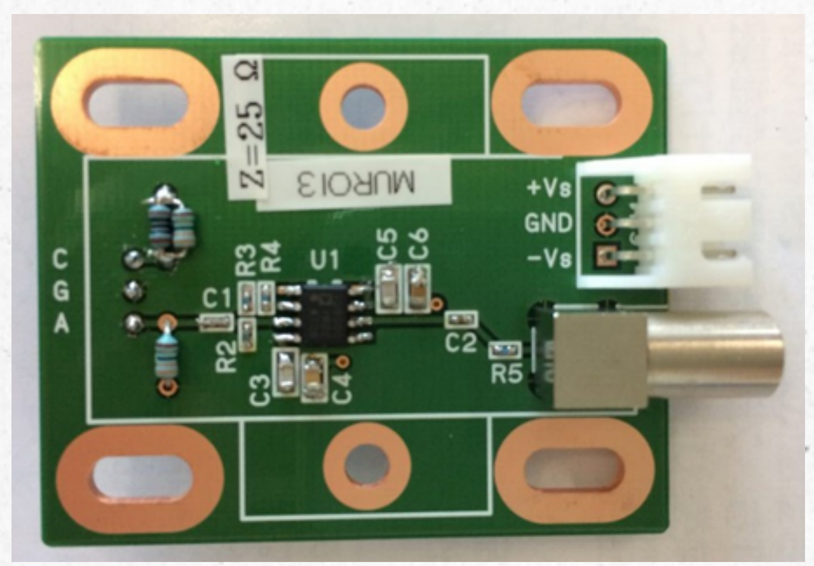


47 cm × 3.5 cm strip
Readout from both ends



0.4th mm soda-lime glass
#2 fish line (∅ 0.23mm)
5-gap and double-stack

Gas:
R-134a+SF_6 (90:10)



Test version of Pre-AMP

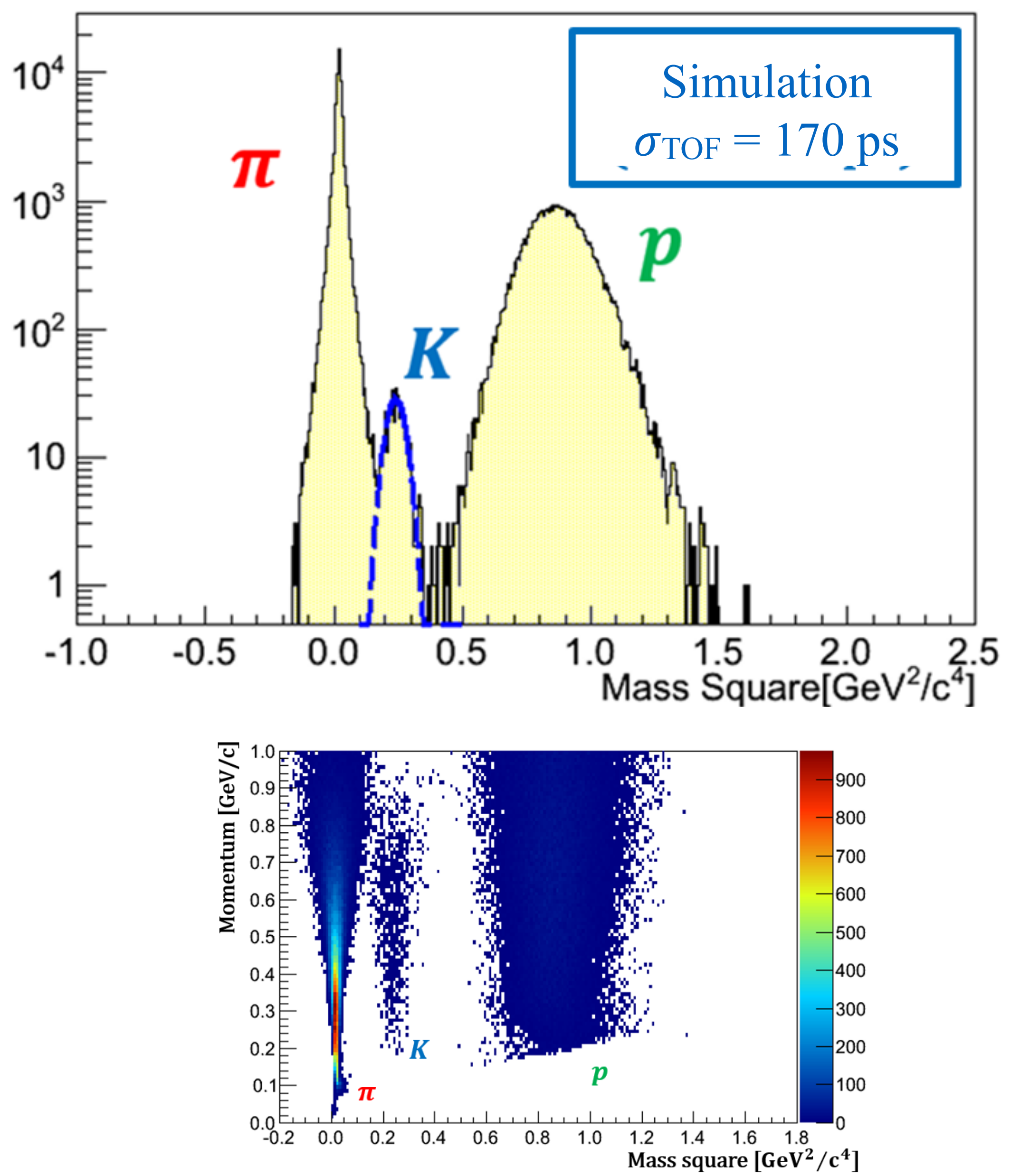
- Impedance matching
- CR differential
- Non-inverse amplifier

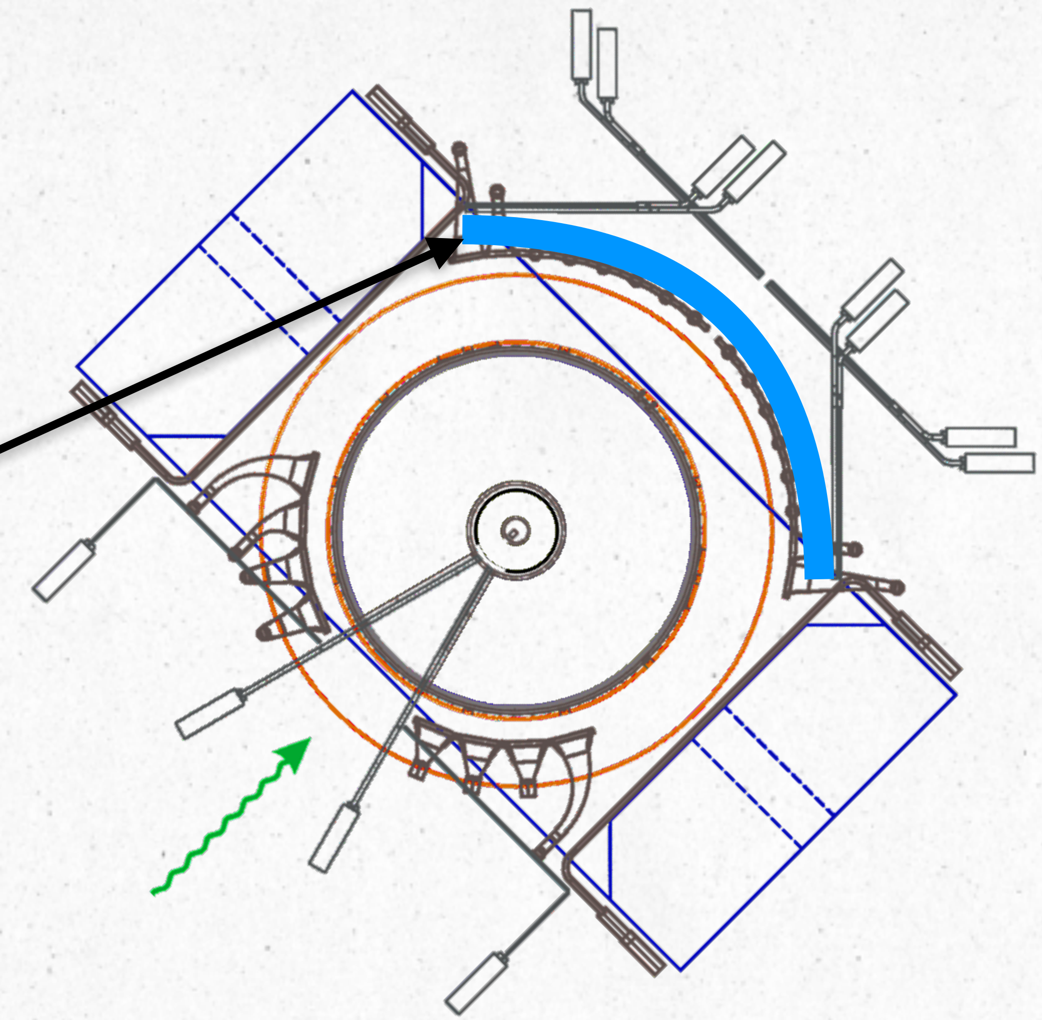
Intrinsic resolution
~120 ps

Particle ID with New Counters

- Add new counters

Expected m² distribution w/ realistic $\pi/K/p$ yield in $\gamma+d$





Aerogel Cherenkov Counter for Electron Veto

- Aerogel
  - n=1.01
    - Japan Fine Ceramic Center
    - Chiba University (Just derived)
- Photon detector
  - SiPM
    - Candidate
      - HAMAMATSU S13360 series MPPC surface mount type
    - Number of photo-electrons (NPE): ~16
      - photon detection efficiency is considered
    - Confirmed enough NPE by cosmic-ray test
      - PMTs are used in the test
  - Amp, HV supply, connection
    - R&D started

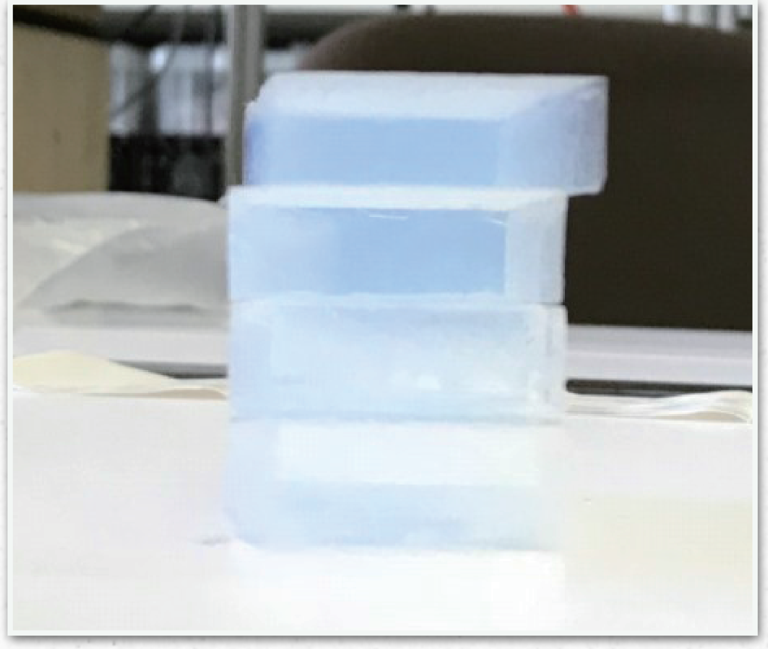
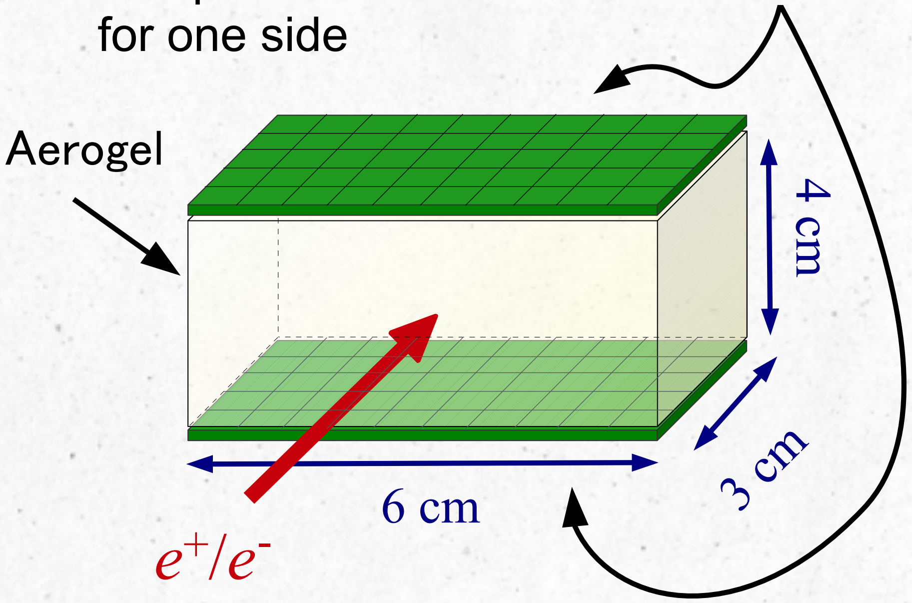


Photo: JFCC aerogel (n=1.01)



Summary of Λn FSI Experiment

- Λn interaction
  - One of keys to understand YN interaction
    - Mass difference of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He
      - Λp and Λn are the same?
      - the other effect?
- Upgrade of NKS2 with new detectors
  - measurement of Λn interaction via FSI effect in $\gamma d \rightarrow K^{+}\Lambda n$ reaction
  - Mass production of new TOF counter (MRPC) will be started soon
  - R&D of the ACC for electron veto is in progress

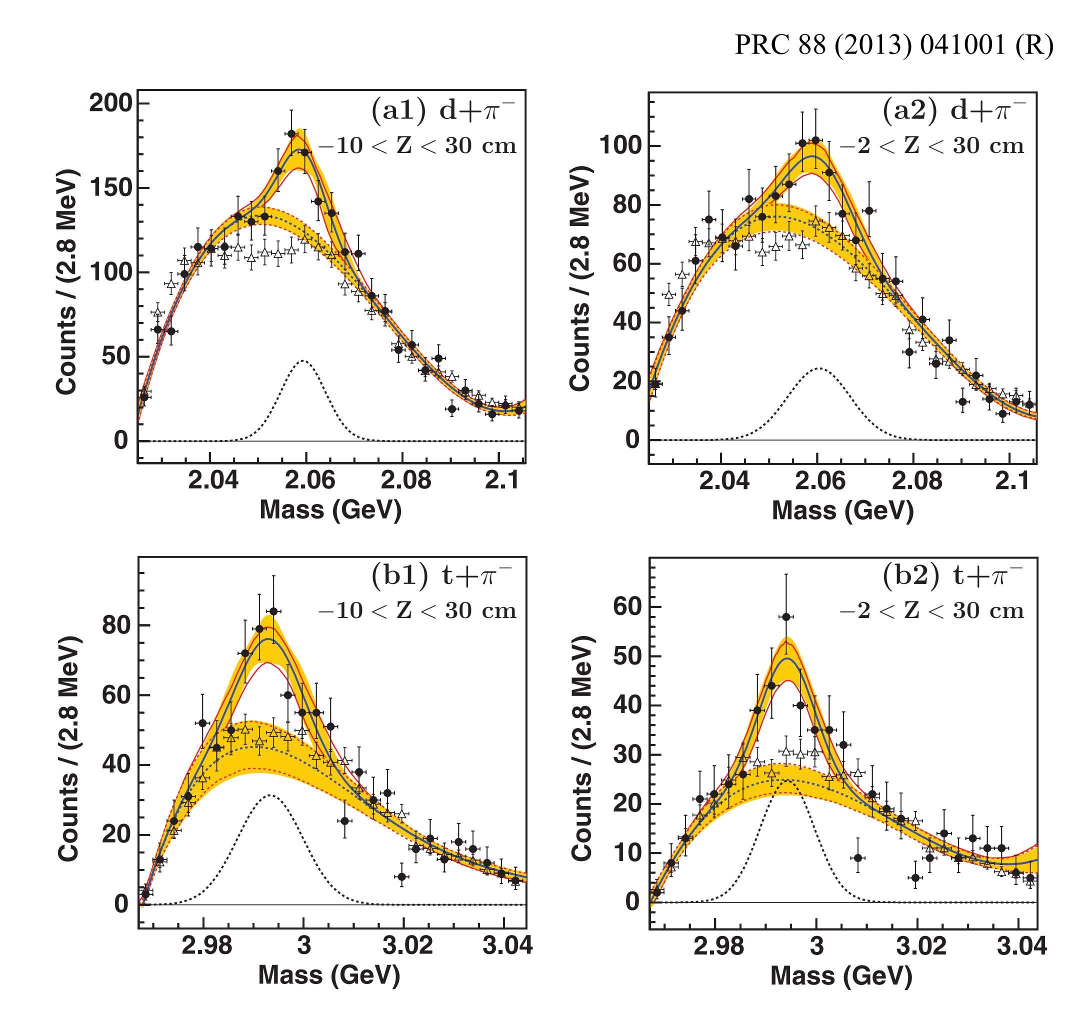
This work are supported by
- JSPS KAKENHI Grant-in-Aid for Scientific Research (B) 18H01220
- MEXT KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas 6007
- JSPS KAKENHI Grant-in-Aid for Scientific Research (A) 17H01121
- Japan-Germany Research Cooperative Program JSPS/DAAD PPP, Germany 57345295.

The Other Projects

- Jefferson Lab
  - Hall A collaboration
    - nnΛ search in $e^- + {}^3\mathrm{H} \rightarrow e^- + K^+ + \mathrm{X}$
      - Ph.D candidate: Kousuke Itabashi (D1)
    - APEX (Dark photon A' search)
    - Iso-spin dependence ΛN by ${}^{40}_{\Lambda}$K, ${}^{48}_{\Lambda}$K Hypernuclei
      - Ph.D candidate: Keita Uehara (M2)
- Mainz
  - Precise measurement of beam energy
- ELPH
  - Modification of NKS2
    - Lifetime measurement of ${}^{3}_{\Lambda}$H
      - $\gamma + {}^3\mathrm{He} \rightarrow K^+ + {}^{3}_{\Lambda}\mathrm{H}$
      - Ph.D candidate: Yuichi Toyama (D2)

nnΛ Search

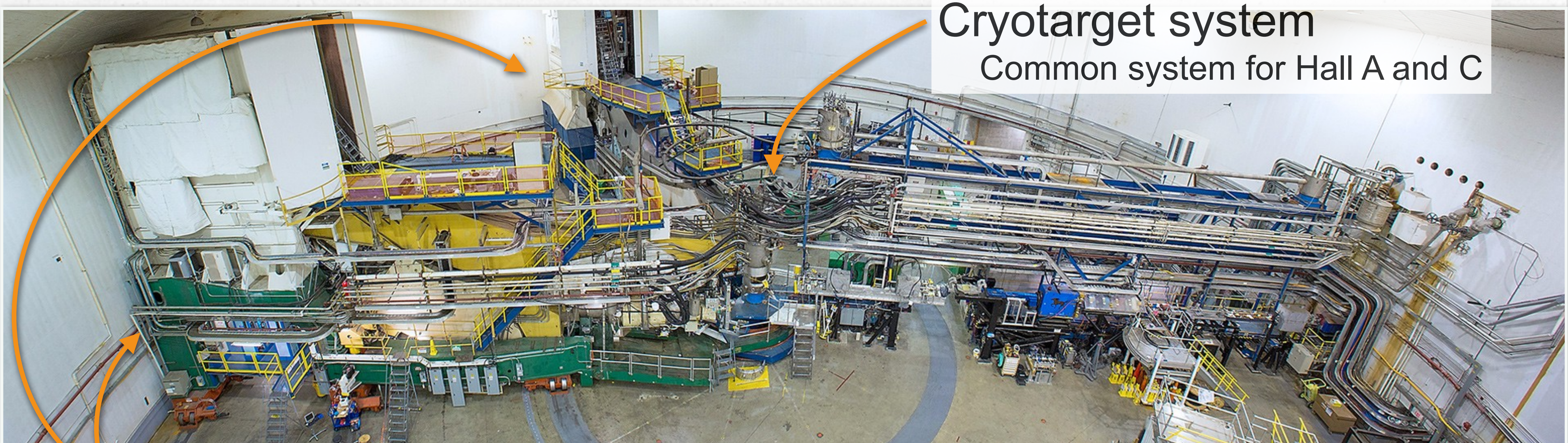
- HypHI collaboration
  - ^{6}Li + C collisions
    - Invariant mass distributions of $d + \pi^-$ and $t + \pi^-$
    - PRC 88 (2013) 041001 (R) reported
      - “the analyses and discussions of the observed final stats of $d + \pi^-$ and $t + \pi^-$ that might be associated with $^3{}_\Lambda n$”



- nnΛ search at JLab
  - Tritium campaign
    - Period: 2017 - 2018
    - Gas ^{3}H, ^{2}H, H, ^{3}He, target
    - Experiments
      - EMC effect for ^{3}H and ^{3}He
      - Isospin dependence of two-nucleon short range correlations
      - Quasi-elastic scattering to measure *p* and *n* momentum distribution
      - Charge radius of ^{3}H and ^{3}He
      - nnΛ search by (e, e’K+) reaction

JLab Hall A

Photo from https://www.jlab.org/research/hall-a

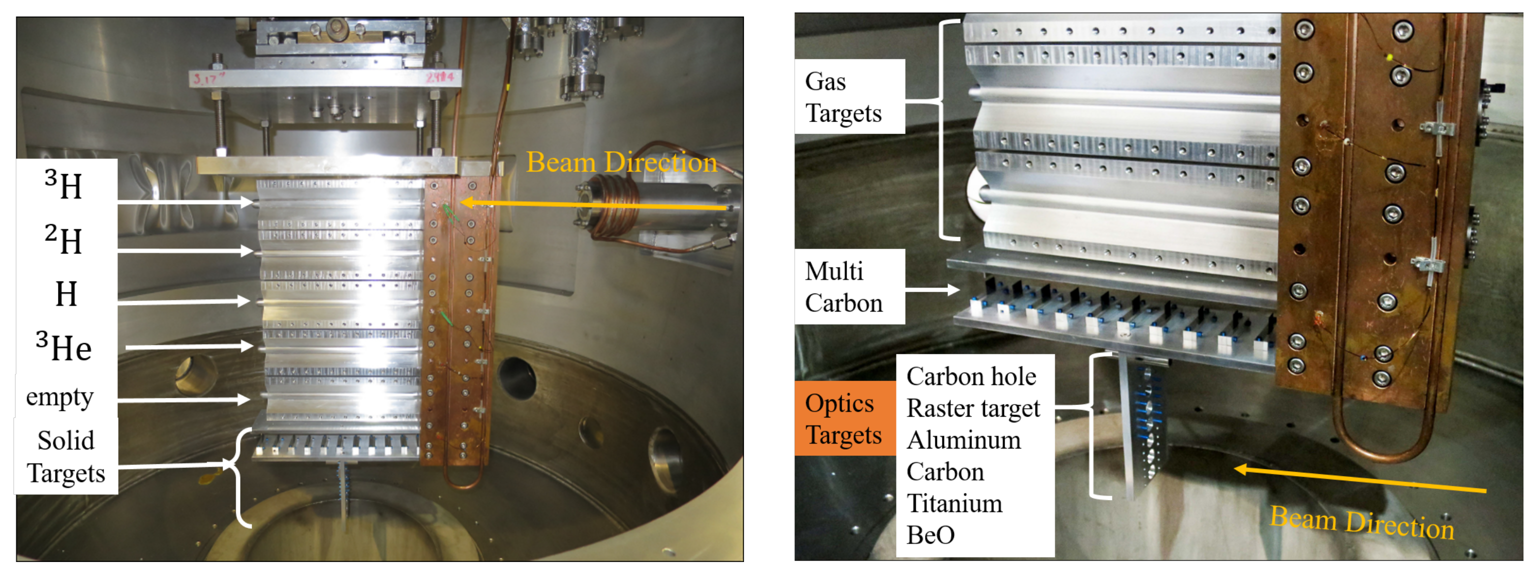


Cryotarget system

Common system for Hall A and C

High Resolution Spectrometer (HRS)

- Magnet config.: QQDQ
- Momentum range: 0.3 - 4.0 GeV/c
- Momentum acceptance ± 4.5%



Targets during the tritium campaign

JLab

Map from JLab web page

Continuous Electron Beam Accelerator Facility (CEBAF)
at Thomas Jefferson National Accelerator Facility

Measurement

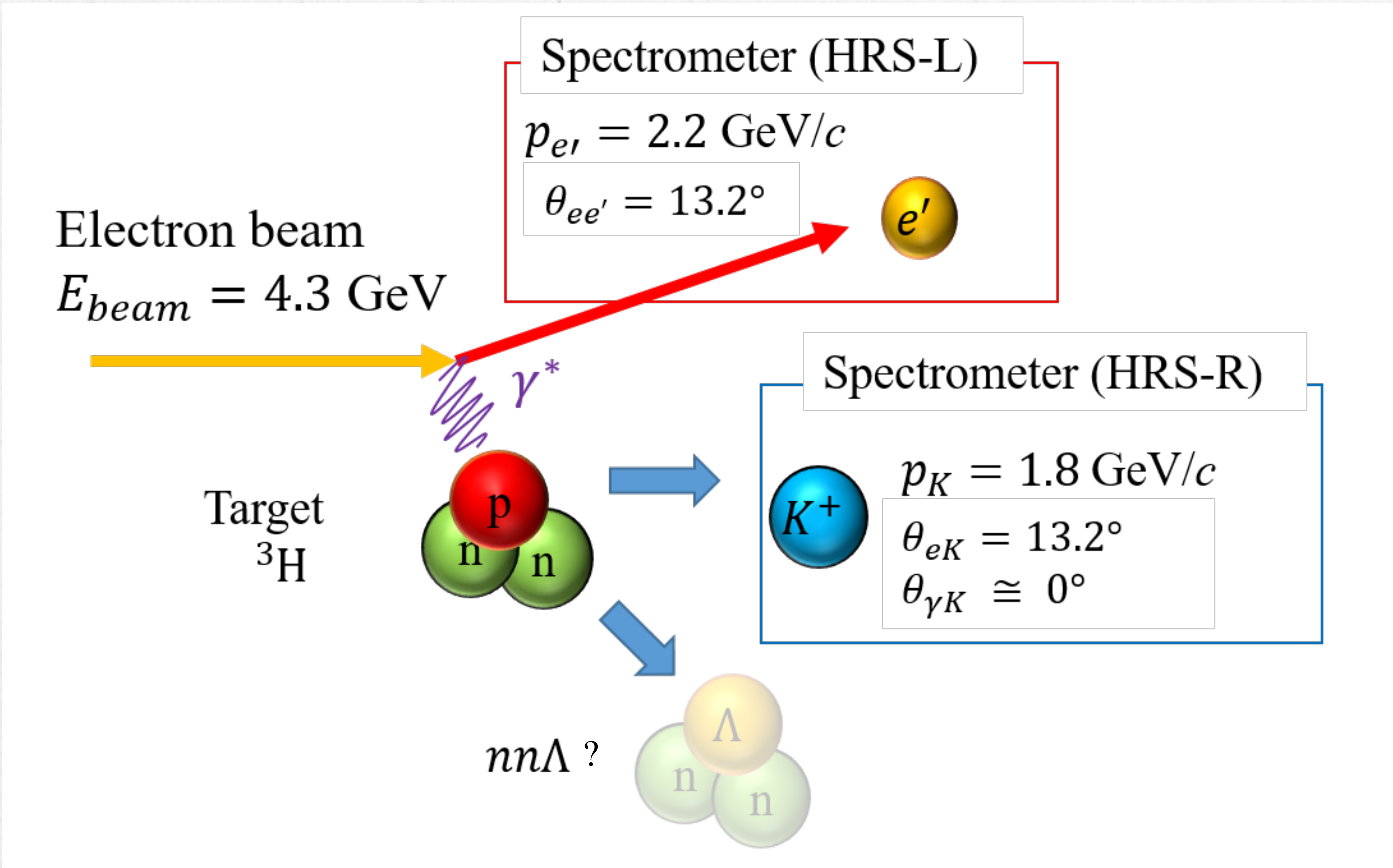
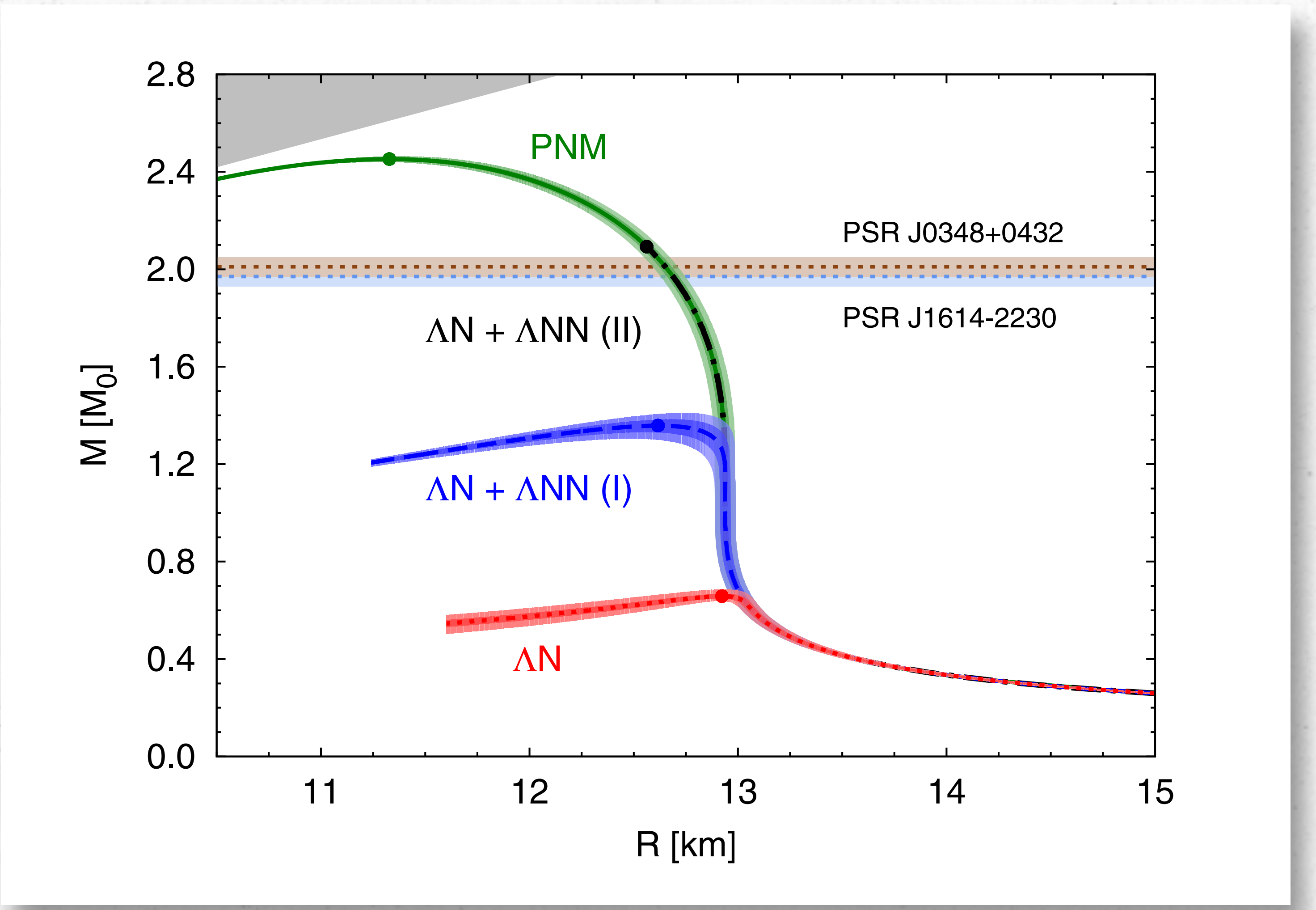


Figure from
K. Itabashi's
Master's thesis
(slightly modified)

- Analysis is in progress

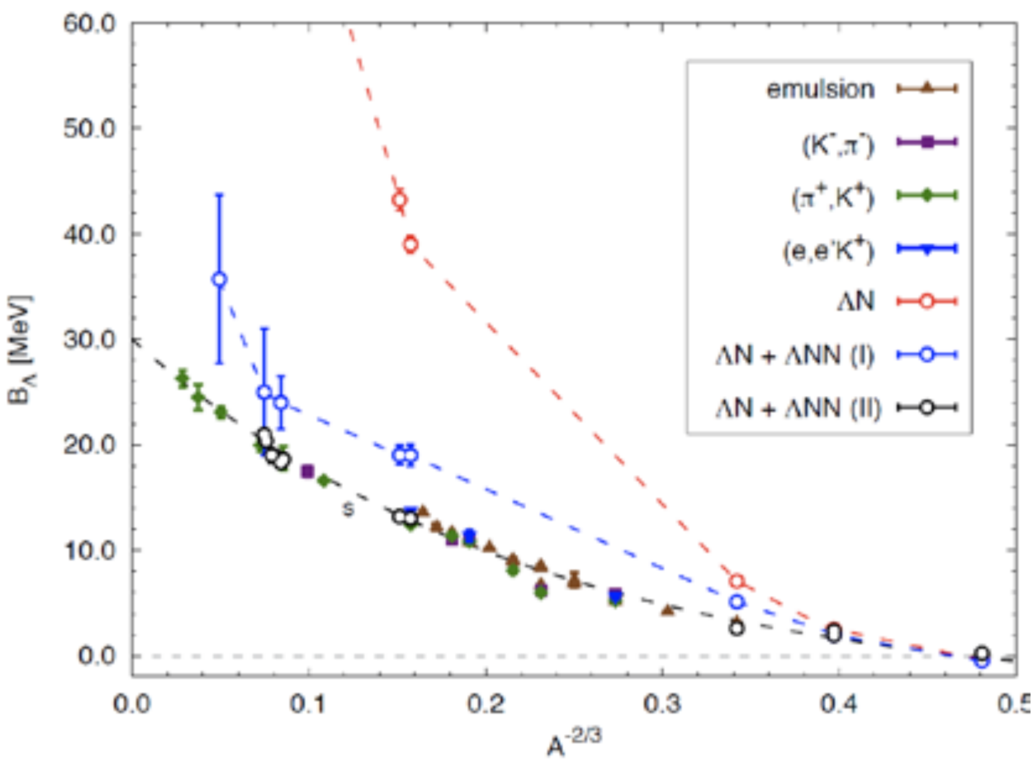
Hyperon Puzzle

- Neutron star
  - EOS base on 2-body YN interaction can not explain two-solar-mass neutron star
  - 3-body ΛNN force is needed



D. Lonardoni et al.
PRL 114 (2015)092301

3-body force in Hypernuclei



Updated from D. Lonardoni et al. PRC 89 (2014) 014314

Note: ΛN interaction is based on Λp data

Parameter C_T gauges the strength and the sign of isospin triplet contribution

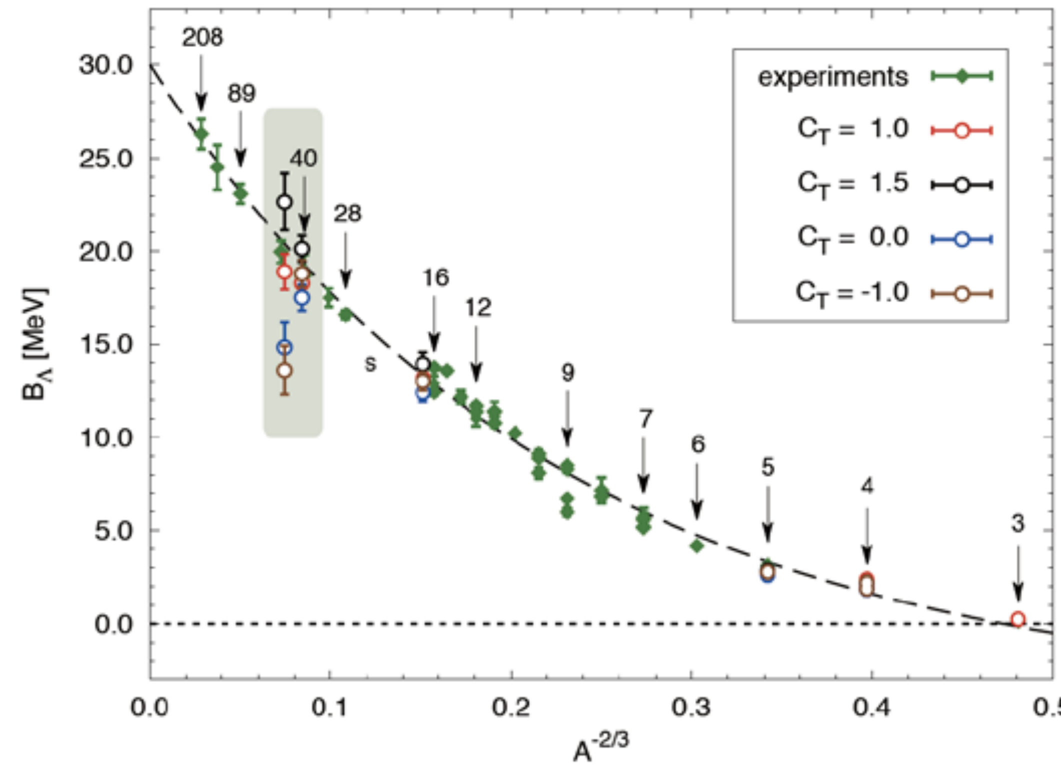
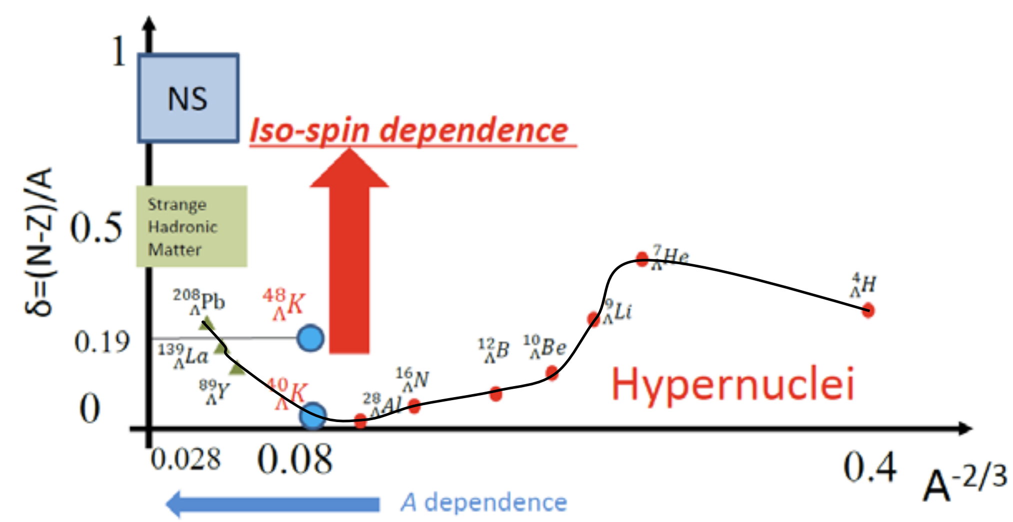
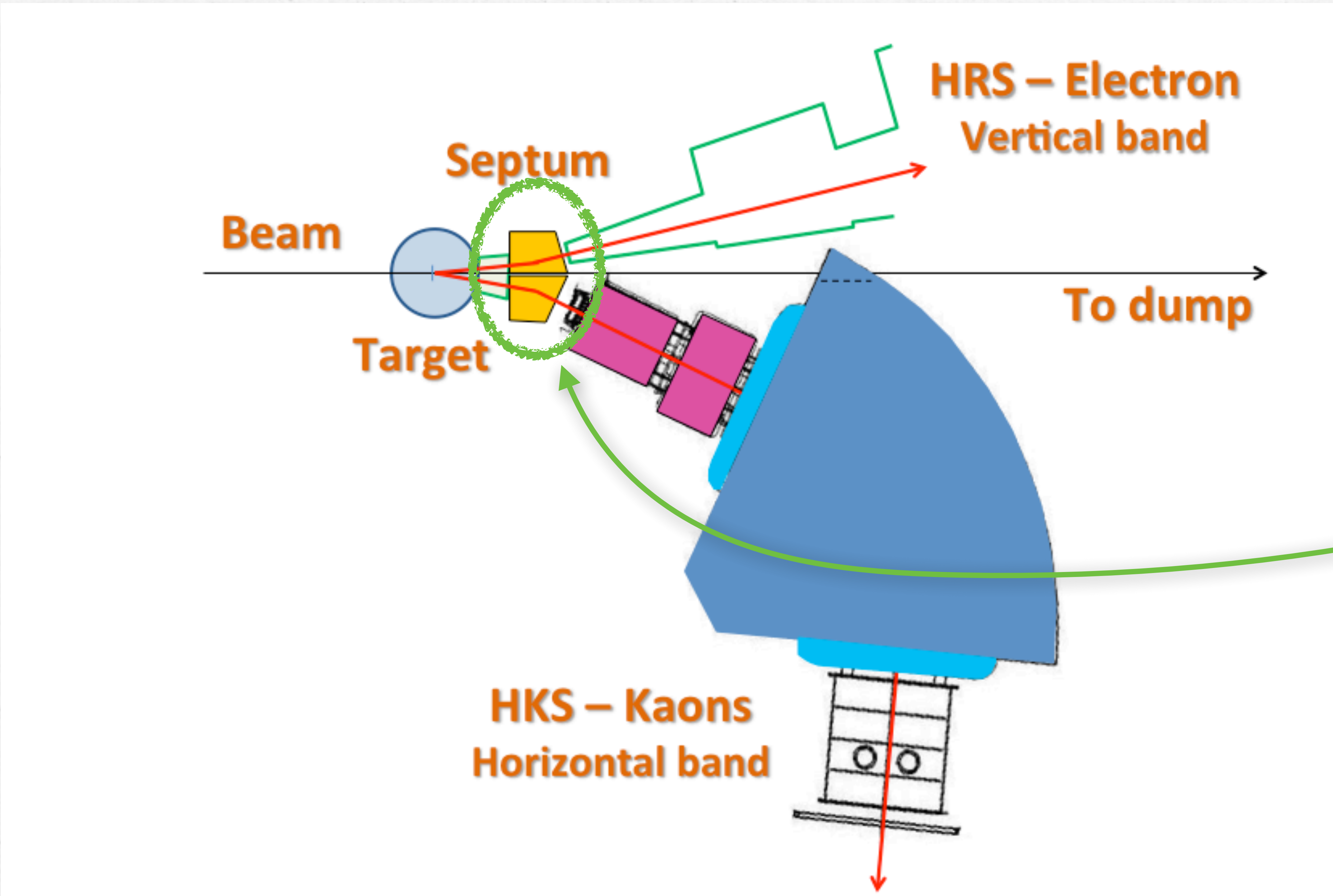


Figure from the proposal, calculation: arXiv:1506.04042.



Setup

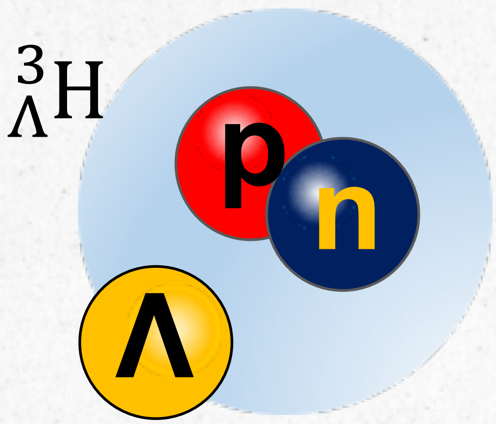


Two magnets in design

Figure from proposal

Lifetime of Light Hypernuclei

- $^{3}_{\Lambda}$H puzzle



B_Λ~0.13 MeV[1]
($^{4}_{\Lambda}$H : B_Λ=2.12 MeV[2])

τ = ~200 ps
(τ_Λ =263 ps)

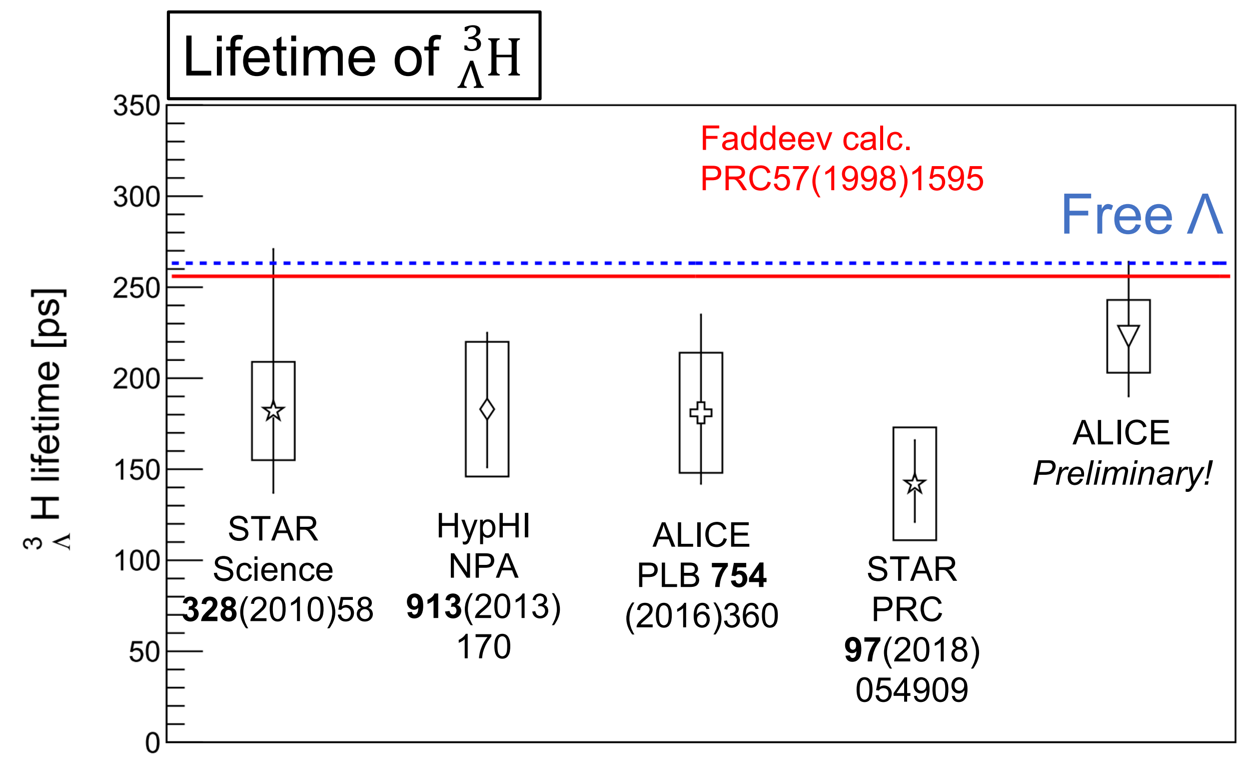


Figure from Y. Toyama's talk in JPS meeting

Small Λ biding energy
Shorter hypernuclei lifetime than free space Λ
} Difficult to explain simultaneously

[1] M.Juric *et al.*, Nucl. Phys. **B 52** (1973) 1-30
[2] S.Nagao, Doctoral thesis 2015 Tohoku University,
A.Esser, S.Nagao, F.Schulz *et al.*, Phys. Rev. Lett. **114** (2015)222501.

${}^{3}_{\Lambda}$H Lifetime Measurement at ELPH

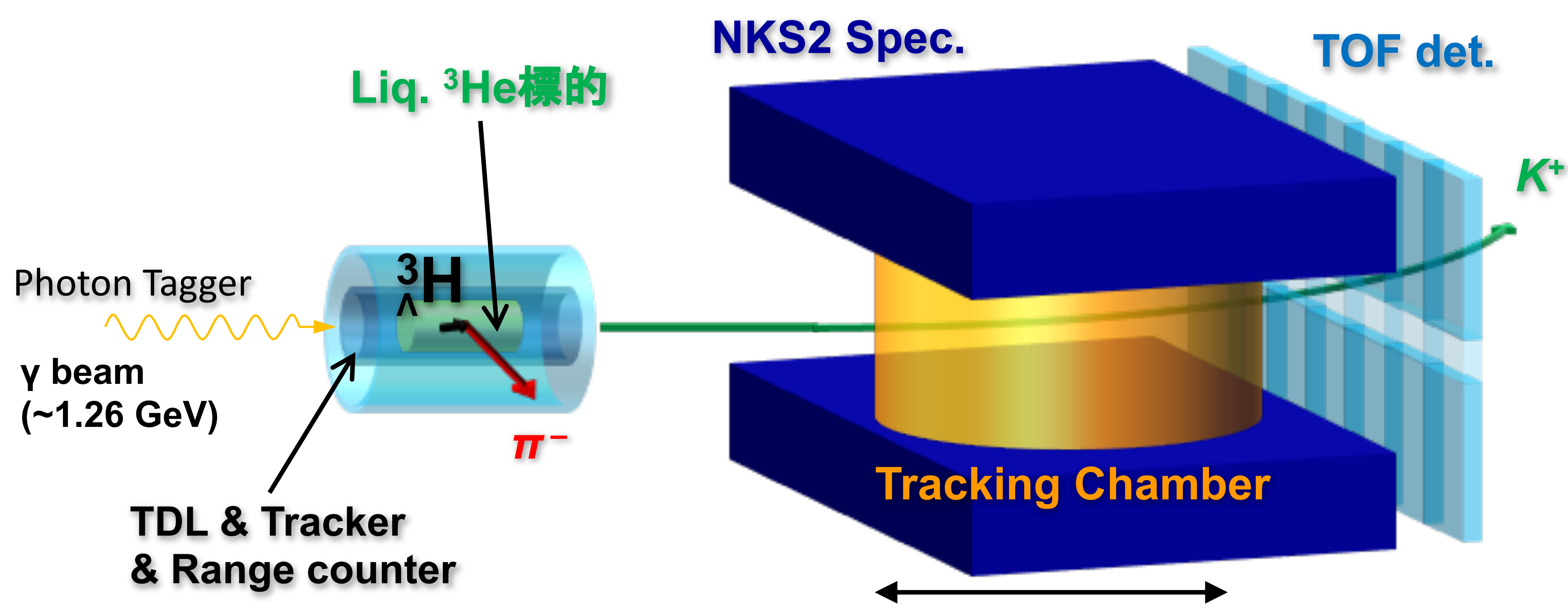
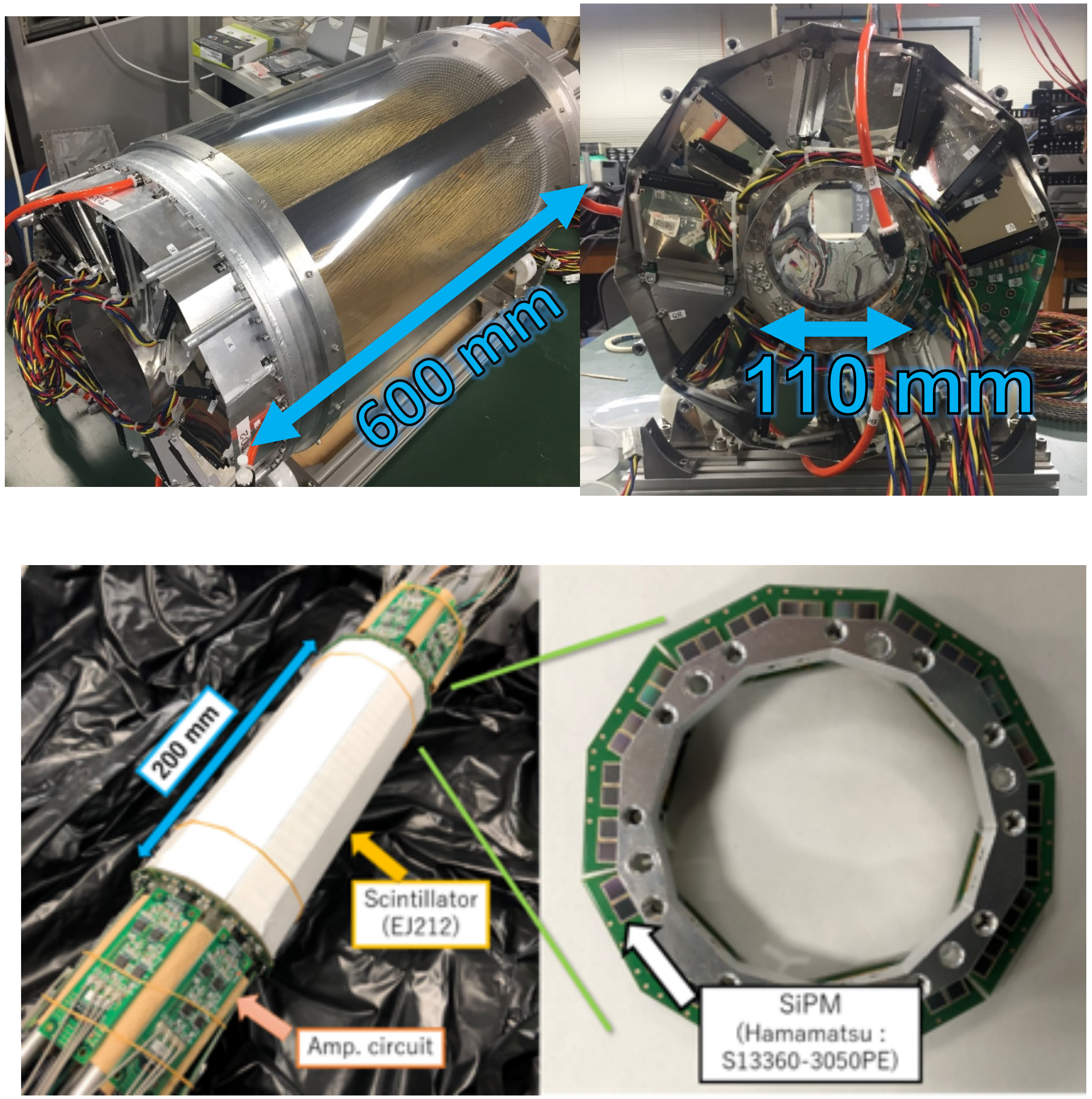
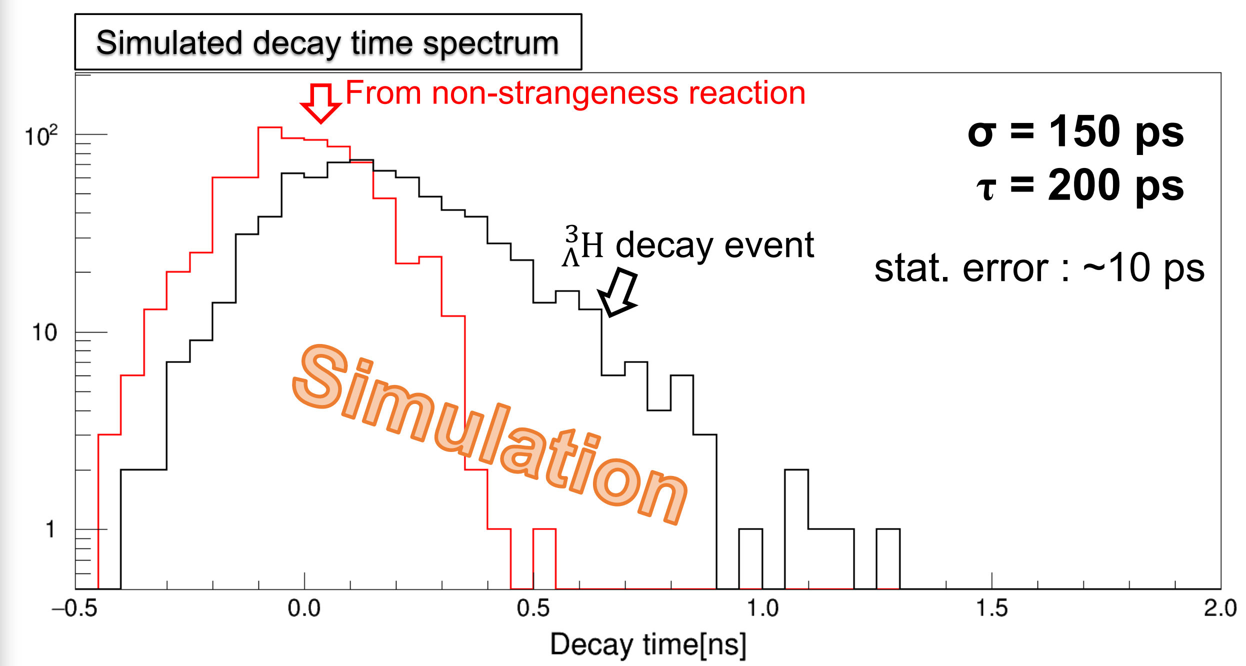


Figure from Y. Toyama’s talk in JPS meeting

- K^{+} ID and momentum
  - NKS2 spectrometer + new TOF
- π^{-} decay time
  - TDL: Timing counter for Direct Lifetime measurement of hypernuclei

Decay Time Measurement





Summary

- Λn interaction measurement by FSI
  - Key of understanding ΛN interaction
  - $\gamma + d \rightarrow K^{+} \Lambda n$ reaction
  - Preparing for the start of 2020
- The other projects
  - nnΛ
    - Analysis is in progress
  - $^{40}_{\Lambda}$K, $^{48}_{\Lambda}$K: isospin dependence of ΛNN force
    - 2021 start (?)
  - Decay pion spectroscopy
  - $^{3}_{\Lambda}$H lifetime
    - 2020 start

Back up

Study about Λp Interaction

Eur. Phys. J. A **21**, 313–321 (2004)
DOI 10.1140/epja/i2003-10203-3

THE EUROPEAN PHYSICAL JOURNAL A

Analysis of the Λp final-state interaction in the reaction p + p ⟶ K$^+$(Λp)

F. Hinterberger[1,a] and A. Sibirtsev[2,3]

2.2 Final-state interaction

In the Watson-Migdal approximation [38–40] the FSI is taken into account by introducing a FSI enhancement factor $|C_{\mathrm{FSI}}|^2$,

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega_K \mathrm{d}M_{\Lambda p}} = |\mathcal{M}|^2 \, |C_{\mathrm{FSI}}|^2 \, \Phi_3, \qquad (3)$$

where now $\mathcal{M}$ is a pure production matrix element and the FSI amplitude C_{FSI} depends on the internal momentum q of the Λp subsystem. It converges to 1 for $q \to \infty$ where the S-wave FSI enhancement vanishes.

$$C_{\mathrm{FSI}} = \frac{q - i\beta}{q + i\alpha}, \qquad |C_{\mathrm{FSI}}|^2 = \frac{q^2 + \beta^2}{q^2 + \alpha^2}. \qquad (4)$$

The potential parameters α and β can be used to establish phase-equivalent Bargmann potentials [44,45]. They are related to the scattering lengths a, and effective ranges r of the low-energy S-wave scattering

$$\alpha = \frac{1}{r}\left(1 - \sqrt{1 - 2\frac{r}{a}}\right), \quad \beta = \frac{1}{r}\left(1 + \sqrt{1 - 2\frac{r}{a}}\right). \qquad (5)$$

The Λp system can couple to singlet $^1S_0$ and triplet $^3S_1$ states. Near production threshold the singlet-triplet transitions due to the final-state interaction cannot occur. Therefore, the contributions of the spin-singlet and spin-triplet final states can be added incoherently. Taking the spin-statistical weights into account the unpolarized double differential cross-section may be written as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega_K \mathrm{d}M_{\Lambda p}} = \Phi_3 \left[0.25\, |\mathcal{M}_s|^2 \frac{q^2 + \beta_s^2}{q^2 + \alpha_s^2} + 0.75\, |\mathcal{M}_t|^2 \frac{q^2 + \beta_t^2}{q^2 + \alpha_t^2} \right]. \qquad (6)$$

This equation leaves six free parameters, the singlet and triplet potential parameters α_s, β_s, α_t, β_t and the production matrix elements $|\mathcal{M}_s|$ and $|\mathcal{M}_t|$. Instead of the parameters α_s, β_s, α_t and β_t one can equally well use the singlet and triplet scattering length and effective-range parameters a_s, r_s, a_t and r_t. The functional dependence on the invariant mass $M_{\Lambda p}$ can be evaluated by inserting the corresponding expression for the internal momentum q of the Λp system,

$$q = \frac{\sqrt{M_{\Lambda p}^2 - (m_\Lambda + m_p)^2}\sqrt{M_{\Lambda p}^2 - (m_\Lambda - m_p)^2}}{2M_{\Lambda p}}. \qquad (7)$$

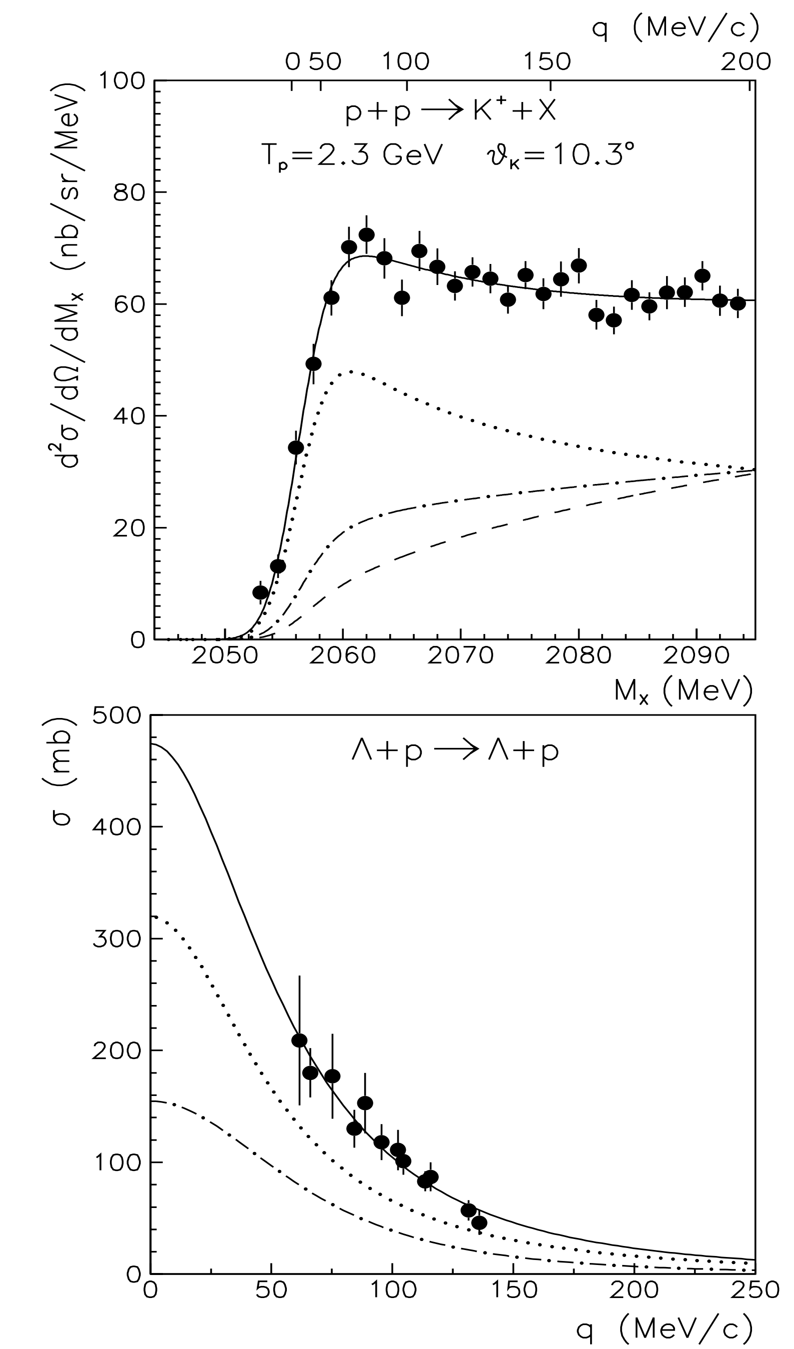


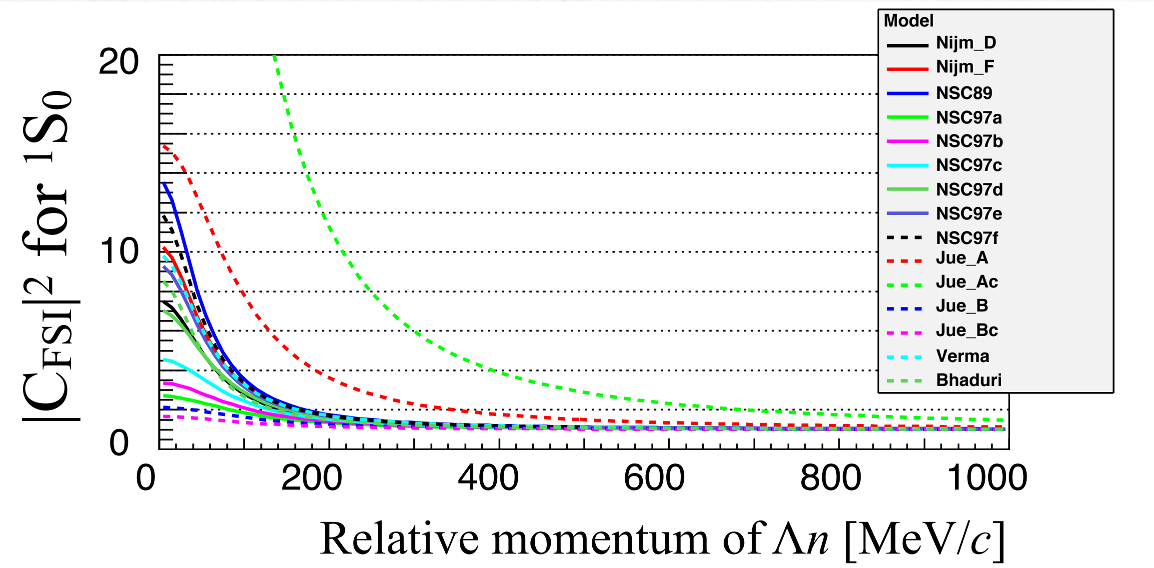
Fig. 4. Same as in fig. 1. Solid lines: Fit curves with parameters given by eq. (15) from a combined five-parameter fit of the missing-mass spectrum and the total-cross-section data, dashed line: phase space distribution, dotted lines: singlet contributions, dash-dotted lines: triplet contributions.

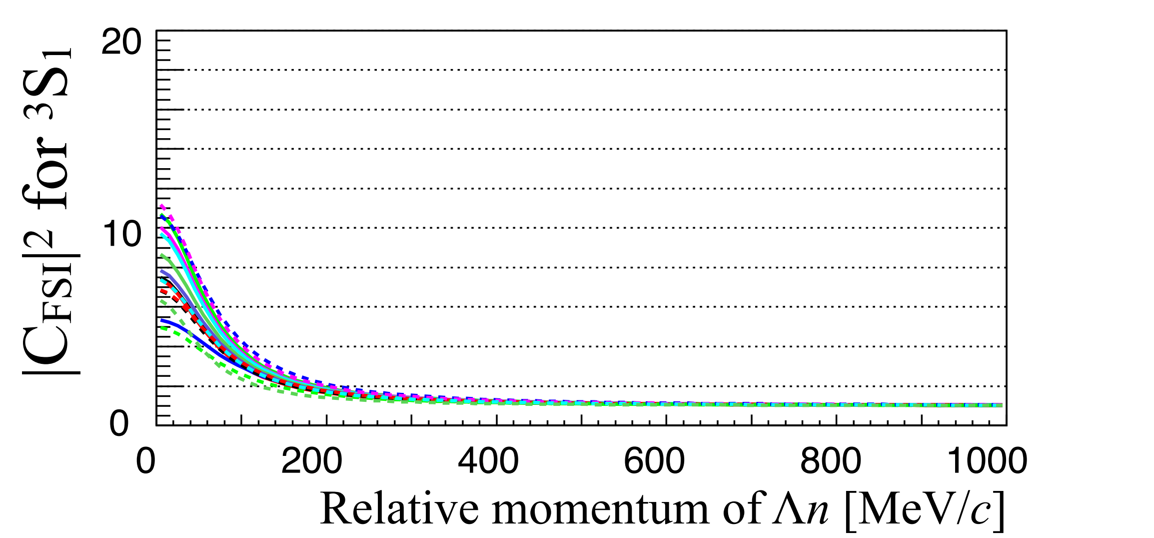
Enhancement Factors of Λn FSI

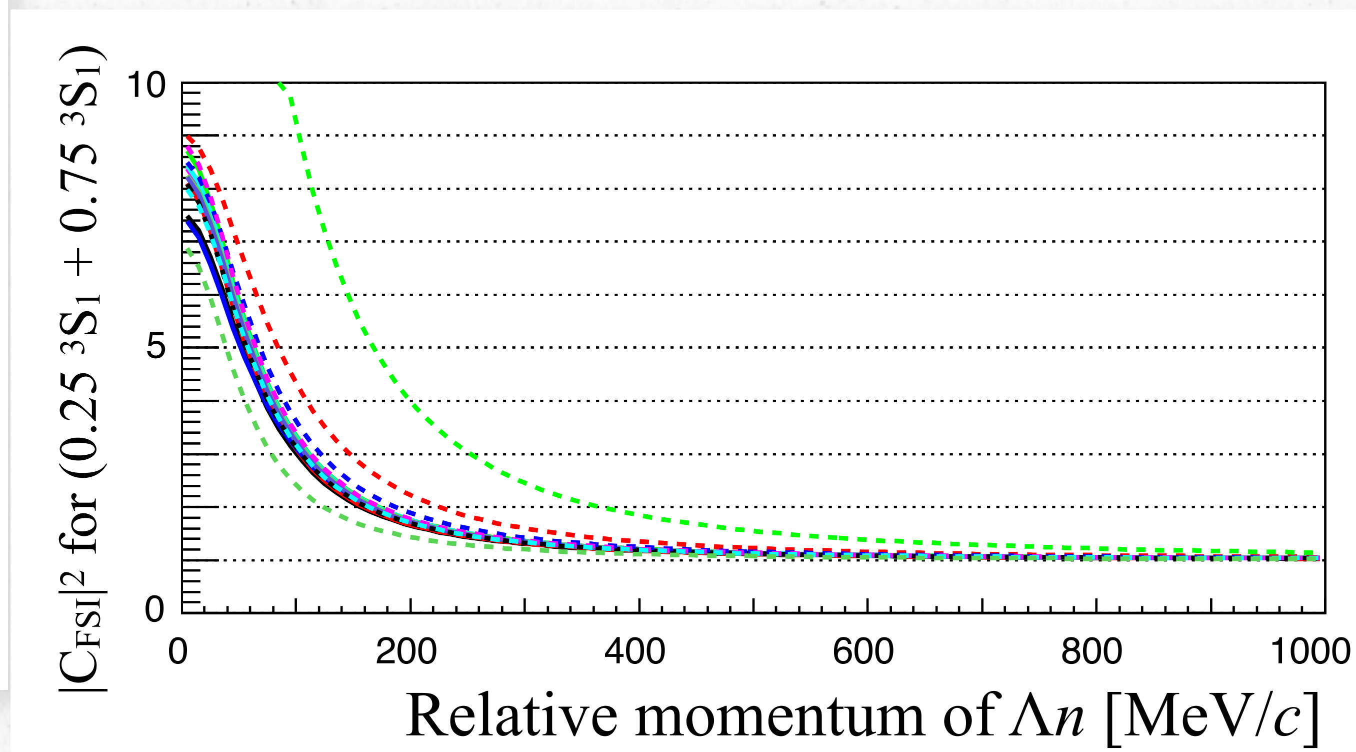
$$|C_{\mathrm{FSI}}|^2 = \frac{q^2+\beta^2}{q^2+\alpha^2}.$$

$$\alpha = \frac{1}{r}\left(1-\sqrt{1-2\frac{r}{a}}\right), \quad \beta = \frac{1}{r}\left(1+\sqrt{1-2\frac{r}{a}}\right).$$

	Refs.	a_s [fm]	r_s [fm]	a_t [fm]	r_t [fm]
Nijmegen D	PRD15 (1977) 2547	-2.03	3.66	-1.84	3.32
Nijmegen F	PRD20 (1979) 1633	-2.4	3.15	-1.84	3.37
NSC89	PRC40 (1989) 2226	-2.86	2.91	-1.24	3.33
NSC97a	PRC59 (1999) 3009	-0.77	6.09	-2.15	2.71
NSC97b		-0.97	5.09	-2.09	2.8
NSC97c		-1.28	4.22	-2.07	2.86
NSC97d		-1.82	3.52	-1.94	3.01
NSC97e		-2.24	3.24	-1.83	3.14
NSC97f		-2.68	3.07	-1.67	3.34
Jülich A (ΛN)	NPA570 (1994) 543	-1.56	1.43	-1.59	3.16
Jülich A~ (ΛN)		-2.04	0.64	-1.33	3.91
Jülich B (ΛN)		-0.56	7.77	-1.91	2.43
Jülich B~ (ΛN)		-0.4	12.28	-2.12	2.57
Verma	PRC22 (1980) 229	-2.29	3.14	-1.77	3.25
Bhaduri (Set I, ΛN)	PR 155 (1967) 1671	-2.46	3.87	-2.07	4.5







Note: It is assumed that the production matrix of single and triplet are the same.

FSI Effect in the K+ Cross-section

- The shape of the curves
  - Enhancement in forward K^+
  - variations: order of 10%
- Highly accurate measurements are required
  - in order to be able to distinguish among different potential models

R.A. Adelseck and L.E. Wright, Phys. Rev **C39** (1989) 580

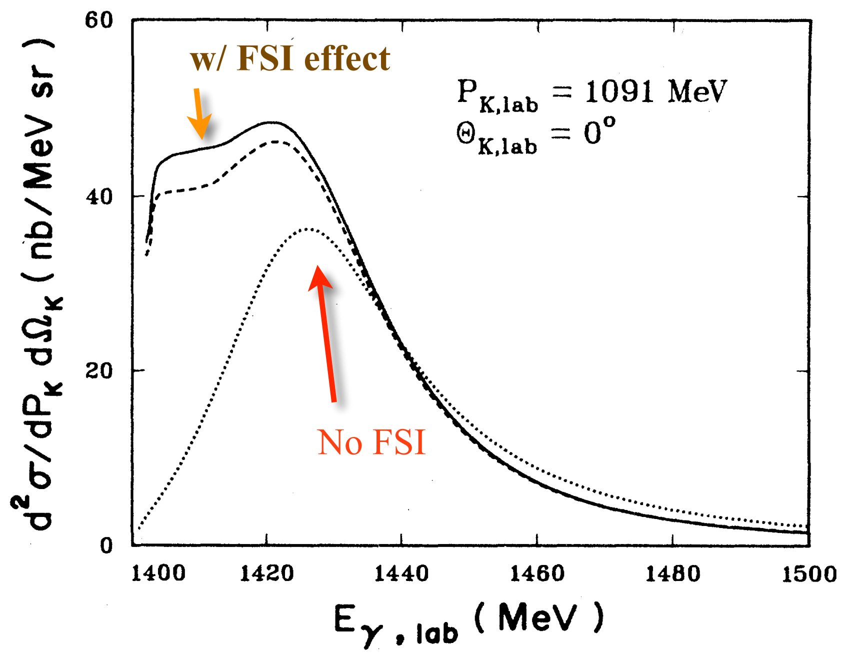


FIG. 8. Comparison of $d^2\sigma$ using the ΛN potential by Bhaduri *et al.* (— — —), the potential by Verma and Sural (——), and the plane-wave approximation (· · ·).

H.Yamamura et al., Phys. Rev **C61** (1999) 014001

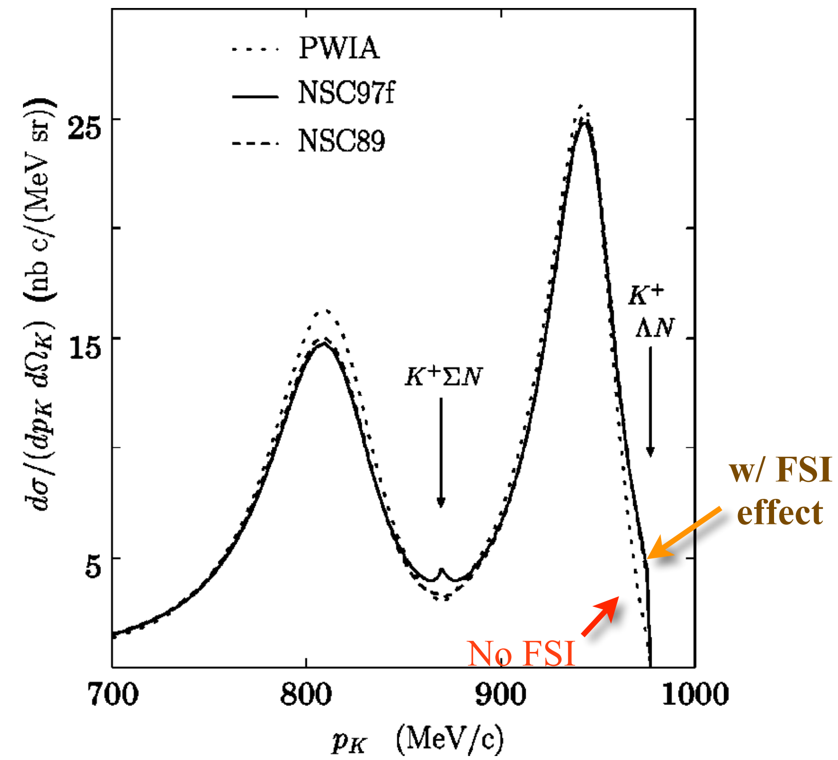


FIG. 2. The inclusive $\gamma(d,K^+)$ cross section as a function of lab momenta p_K for $\theta_K=0°$ and photon lab energy $E_\gamma=1.3$ GeV. The plane wave result is compared to two YN force predictions. The FSI effects are especially pronounced near the $K^+\Lambda N$ and $K^+\Sigma N$ thresholds, the locations of which are indicated by the arrows.